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# FINAL REPORT

# THE OCCURRENCE AND MOBILITY OF HAZARDOUS ORGANIC CHEMICALS IN GROUNDWATER AT SEVERAL ONTARIO LANDFILLS

## LOTTERY TRUST FUND PROJECT 118PL

Report prepared for Environment Ontario by:

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JUNE 1989

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## ENQUIRIES

All enquiries regarding this project should be directed to M.J. Goodwin (Liaison Officer) of the Waste Management Branch or to the Research Coordination Office of the Ministry of the Environment.

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# 1

# EXECUTIVE SUMMARY

## 1.1 Introduction

For the past four years researchers at the Institute for Groundwater Research have been examining the occurrence of organic contaminants in groundwaters at six sanitary landfill sites and at one waste disposal facility in southern Ontario. The purposes were to determine what organics are contaminating groundwaters, how rapidly these contaminants travel in groundwater and how persistent these organics are in the groundwaters. The landfill sites selected represent a variety of hydrogeological conditions and so were expected to be representative of most sanitary landfill sites in southern Ontario. Also, most sites had been previously studied, so that their hydrogeology and some aspects of existing contamination were already known.

At all landfill sites, the organic compounds found in water that percolated through the fill (leachate) were examined and certain common, toxic and readily-analyzed organics were selected for detailed study. Their distribution in groundwaters impacted by leachate were determined by analyzing a large number of groundwaters collected from numerous wells placed to give a good, three-dimensional picture. Sampling was often repeated throughout the study to define the variability of concentrations over time. At most sites a "plume" of contaminated groundwater, not unlike a plume of smoke from a smoke stack, was found to emanate from the landfill site.

It was not the mandate of this study to determine the waste forms or chemistry at each site. Such information is rarely available and is rarely sufficiently reliable to define target organic contaminants. We simply analysed leachate and selected target organics for detailed investigation. At all sites, the organics chosen for the most detailed investigation were of two types:

1. one or two carbon hydrocarbons in which some of the hydrogens are replaced by chloride atoms. This group is called volatile halocarbons and includes such common chemicals as 1,1,1-trichloroethane, trichloroethylene, tetrachloroethylene, chloroform and carbon tetrachloride.
2. hydrocarbons, containing a specific organic structure called a benzene ring, which are volatile or semi-volatile at room temperature. These organics are termed volatile aromatics and include benzene, toluene, xylenes, chlorobenzene, dichlorobenzene and other benzene-like molecules with various substitutions attached to the basic ring. These are petroleum products, common solvents and common industrial chemicals.

Wherever organic contaminants were found in landfill leachate, these two classes of compounds included most of those organics of environmental concern judging by their inclusion in the Ontario Government's Regulation 309 and in the list of one hundred odd organic chemicals included in the U.S. Environmental Protection Agencies list of priority organic pollutants. They are also among the most mobile organics.

Table 1 lists the compounds sought in the groundwaters and the existing drinking water criteria, guidelines or limits where available. It is not our purpose to evaluate toxicity of groundwaters. Rather this table is provided only to indicate organic concentrations of concern in water. Analytical methods and quality assurance data is presented in Appendix D.

## 1.2 The Landfill Sites

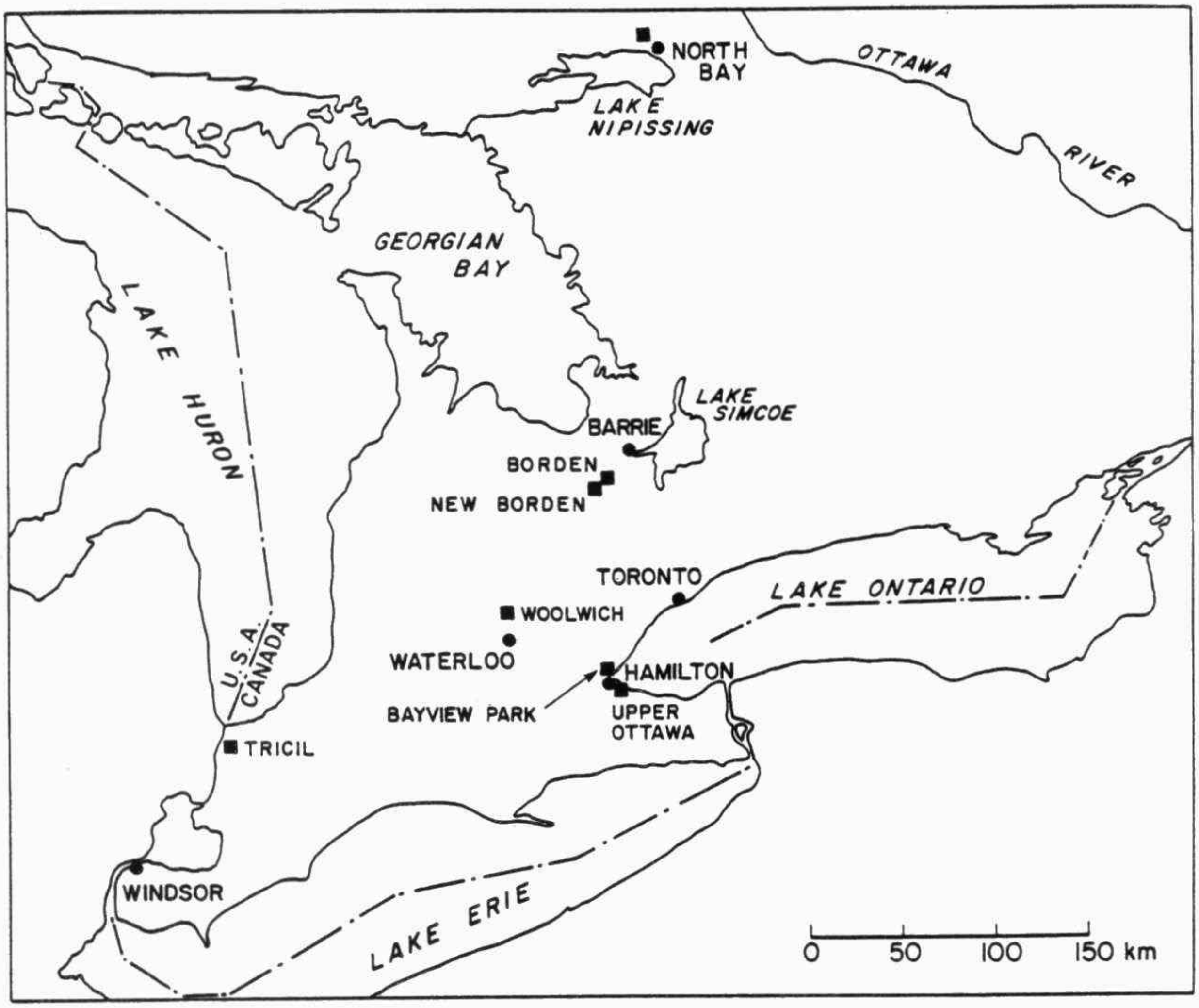
The locations of the landfill sites investigated in this study are shown in Figure 1.1. Three of the sites were located upon permeable, unconsolidated sand deposits in which groundwaters could move laterally quite rapidly (up to 5 m per day). Thus, at the Borden, Woolwich and North Bay sites plumes of groundwater contamination extend for 800 to 1000 m from the sites. The New Borden site is located upon less permeable unconsolidated sandy till material in which groundwater moves laterally at about 25 m per year. Thus the contaminated groundwaters extend less than 250 m from this 10 year old site.

The facility operated by Tricil Limited is situated upon thick clayey deposits and the contamination extends only about 1 m from the waste.

The remaining two sites - Bayview Park and Upper Ottawa Street - are situated upon sedimentary bedrock. Unlike the unconsolidated materials, these are extensively fractured and the fractures, where open, provide the major conduits for groundwater flow. Rather than moving through the mass of interconnected pores as in sands, groundwater flows mostly along interconnected fractures, often bypassing cubic metre volumes of rock. It is much more difficult to anticipate the fracture pathways that contaminants will take and so locating sampling points is much more difficult than for the much more regular mass flow through porous sands or tills.

Studies at all sites except Tricil and Upper Ottawa Street were supported largely by grant RAC 118 from the Ontario Provincial Lottery Trust Fund. Studies at Tricil were mainly supported by an NSERC strategic grant (G1372) and studies at the Upper Ottawa Street site were funded by the Upper Ottawa Street Landfill Site Committee. At all sites the support of Ministry, local government officials and land owners enabled this study to proceed. Their support and the diligent efforts of staff and students in the Earth Sciences Department at the University of Waterloo are gratefully acknowledged.

*Figure 1.1*: The location of study sites (square symbols).



## 1.3 Results from each site

### 1.3.1 Borden Landfill

A plume of contaminated groundwater emanates from beneath this abandoned landfill site and extends over a broad front for about 900 m away from the site in an unconfined sand aquifer at shallow ($< 20$ m) depths. Only a few organic compounds have been identified in the contaminated groundwaters. These include very low concentration ($< 5$ ug $L^{-1}$) of some volatile aromatics and halocarbons, equally low concentrations of organic acids and occasionally some elemental sulphur ($S_8$).

This general lack of organic contaminants probably reflects the innocuous landfilled materials, mainly construction debris, and the practice of regularly burning the refuse. Consequently, it is not possible to evaluate mobility or persistence from the resulting low concentrations of organic contaminants.

### 1.3.2 Woolwich Landfill Site

This site in Waterloo Region has operated since the 1960's and was closed in December 1986. It is located upon permeable sand and gravel deposits. Waste is emplaced 3 to 5 m above the water table and so percolating water must pass through this soil zone before it becomes part of the groundwater system beneath the water table. A plume of contaminated groundwater extends perhaps 1000 m from this site.

Leachate contains high concentrations ($> 1000$ ug $L^{-1}$) of individual organic fatty and aromatic acids - common products of the breakdown of organic matter when oxygen is not present (anaerobic conditions). These are relatively innocuous organics. Of more concern are the tens of ug $L^{-1}$ of halocarbons such as trichloroethylene and chloroform and the hundreds of ug $L^{-1}$ of aromatics such as toluene, ethylbenzene and xylenes and various phenols also present at hundreds of ug $L^{-1}$.

These organics are found in high concentrations only within about 100 m of the landfill site. Beyond about 300 m, these organics are not found above their detection limits (0.1 to 5 ug $L^{-1}$).

Inorganic contaminants such as chloride are also found only at greatly reduced concentrations beyond 300 m of the landfill. This reflects the dilution that occurs as the leachate continuously mixes with natural groundwater as it flows from the landfill site. As in the plume of a smoke stack, this dilution process is termed *dispersion*. In these groundwaters, dispersive dilution accounts for much of the concentration reductions observed for the organic contaminants.

The concentration reduction or *attenuation* for organics appears even greater than would result simply from dispersive dilution. It is inferred than an additional process also influences many of the organics. The most likely process is *biotransformation* or *biodegradation*. Microbes in the aquifer appear to be biotransforming many of the halocarbons and aromatic hydrocarbons into innocuous inorganic products. Thus, both dispersion and biodegradation appear to limit the occurrence of significant organic contaminant concentrations to within 300 m of the site.

### 1.3.3 North Bay Landfill Site

The most extensively studied site is at North Bay. Landfilling since 1962 in an abandoned sandpit has created a plume of leachate in the water table aquifer of unconsolidated sand. The plume extends about 800 m to a series of springs where leachate-impacted groundwater is discharged at the surface near Chippewa Creek. Groundwater moves through this flow system within two to four years so discharge has been occurring for almost twenty years. We are not, therefore, looking at a plume developing, but rather are looking at what an established plume has become over time.

Again, the organic contaminants of most concern are the tens of ug $L^{-1}$ of halocarbons and volatile aromatics, although organic acids again are the dominant organics identified in leachate.

The distribution of these organics and the indicator parameter, chloride, have been reasonably steady over the four years of intensive sampling. This suggests that the addition at the landfill is matched by dilution and biodegradation during flow through the plume. Once again, by the end of the flow system the halocarbons and many aromatics are attenuated even beyond the dilution brought about by dispersion. Biodegradation is the likely processes causing this additional attenuation. This anaerobic biodegradation, much of which occurs under methanogenic conditions, combines with dispersive dilution to produce organic concentrations generally below drinking water standards (Table 1) at the discharge area.

Comparing the distributions of typical leachate indicator parameters with those of specific organic contaminants suggests that these indicator parameters are very useful for identifying the area of contaminated groundwater. However, they are less useful for inferring the level of organic contamination at any point in the contamination plume. In addition, some aromatics are more attenuated than others during transport and so their relative concentrations vary. This suggests that an attempt to follow only certain organics in order to assess the degree of groundwater impact near a landfill site may be misleading, if the selected organics do not persist.

### 1.3.4 Tricil Waste Disposal Facility

The extent of contamination of groundwater at the site was evaluated by analyzing pore water obtained from cores of the clayey deposit below a disposal trench, operated from 1979 to 1980. Although chloride has moved about 90-100 cm in a 5 year period, the most mobile organics (benzene, toluene) had moved less than 30 cm. The transport process appears to be molecular diffusion with some retardation of organics by sorption. The impact of biotransformation is currently being assessed, but it does not appear to be significant.

At this study site it would appear that migration of hazardous organics will be very slow ($< 6$ cm $a^{-1}$) and will be due to molecular diffusion not groundwater advection. While this augurs well for such disposal facilities, it suggests that clay liners will transmit contaminants by diffusion even if no groundwater flow occurs. Liners may only provide a short term protection against the release of low concentrations of mobile organic contaminants.

### 1.3.5 New Borden Landfill

Since 1976 refuse from CFB Borden has been landfilled in a series of three cells on a site underlain by unconsolidated silty sand till, a glacial deposit of slight to moderate permeability. Groundwater within the cells contacts the fill and contaminants leached from the fill have been found up to 200 m from the site.

Again, the major contaminants of concern are found within the halocarbons and volatile aromatic groups. Carbon tetrachloride appears to have migrated as far as chloride, while both 1,1,1-trichloroethane and trichloroethylene are more restricted, probably due to their biotransformation in the shallow flow system. Volatile aromatics such as p- and m-xylene, toluene and 1,2,4-trimethylbenzene also show a migration restricted by biotransformation.

### 1.3.6 Bayview Park Landfill

The 18 ha Bayview Park landfill site is located in Burlington near Lake Ontario. Between 1961 and 1974 waste was deposited in quarry excavations of the underlying Queenston Formation shales. The shale is extensively fractured with horizontal, perhaps bedding plane fractures providing the major flow paths for contaminants. Initial findings are presented by Hewetson (M.Sc. thesis, 1985) and Pankow et al. (1986) and no further discussion of this site is presented here.

### 1.3.7 Upper Ottawa Street Landfill Site

This 50 ha site accepted both municipal and industrial waste from 1954 to 1978. It is located on the Escarpment at Hamilton upon hard cherty dolomite of the Silurian Lockport Formation. Groundwater flows mainly via sub-vertical and sub-horizontal fractures. The distribution of leachate-impacted groundwaters was difficult to define because of:

1. the lack of unique organics in the leachate
2. the often poor, but variable natural groundwater quality, and
3. the complex pattern of groundwater flow possible in such fractured systems.

Leachate again is dominated by organic acids, with surprising low concentrations of organics of obviously industrial origin. Natural groundwaters seem to be a mixture of two types. One, high in most inorganics and containing a few ug $L^{-1}$ of volatile aromatics probably represents very old water present in the bedrock. The other type is much lower in most inorganics and organics and is probably much more recently recharged. A series of statistical tests was applied to identify those groundwaters impacted by landfill leachate. Even so, leachate impact could not be very reliably identified.

The movement of leachate in the fractured bedrock appears to have produced an erratic, but restricted zone of groundwater contamination. Most leachate contamination occurs within 100 m of the landfill or to the east along the general groundwater flow direction. Leachate does not appear to have caused a major impairment in water quality, especially given the poor water quality present naturally.

## 1.4 Overall Observations

### 1.4.1 Organics Occurring in Landfill Leachate Plumes

The dominant organics found in the landfill leachate plumes were various acids - common products of anaerobic breakdown of refuse and of little environmental concern. Most organics of concern are halocarbons and volatile aromatics. All landfills, irrespective of location or hydrogeological setting, have rather similar organics of concern. This must reflect their ubiquitous occurrence in landfilled material and reasonable availability to infiltrating waters.

### 1.4.2 Organic Contaminant Mobility and Persistence

In all landfill leachates except that in clayey till, the halocarbons and volatile aromatics appear to be very mobile, migrating at almost the same rate as the groundwater itself. This probably reflects the minimal *retardation* of organics normally brought about by sorption of the organics onto aquifer materials. Such minimal sorptive retardation is expected for these aquifers containing little solid organic matter - the major sorptive phase for these organic contaminants. The clayey till of the Tricil site shows greater sorptive retardation of organics.

The apparent persistence of organics appears to be limited by two processes - dispersive dilution and biotranformation. Dispersive dilution affects all leachate chemicals and brings about 30% to 90% concentration decreases in the landfill leachate plumes examined in this study. In addition, for many of the halocarbons and volatile aromatics, biotransformation appears to have brought about even greater restrictions in the distributions of organics of concern.

Such biotransformation processes are poorly understood in general and difficult to quantitatively document even in this study. They do seem to offer considerable benefit in limiting the impact of landfill leachate organics upon groundwater quality and so warrant further research aimed at a predictive understanding of these biotransformation processes.

*Table 1.1*: Drinking Water Guidelines and Standards for Selected Organic Contaminants

***Halocarbons***

| | | WHO$^{a}$ | EPA$^{b}$ ug L$^{-1}$ | STATE |
|---|---|---|---|---|
| ***Methanes*** | | | | |
| Chloromethane | $CH_3\ Cl$ | | | |
| Bromomethane | $CH_3\ Br$ | | | |
| Dichloromethane, methylene chloride | $CH_2\ Cl_2$ | | | |
| Dibromomethane, methylene bromide | $CH_2\ Cl_2$ | | | |
| Dibromochloromethane | $CH\ Br_2\ Cl$ | | | |
| Bromodichloromethane | $CH\ B\ Cl_2$ | | | |
| Tribromomethane, bromoform | $CH\ Br_3$ | | | |
| Trichloromethane, chloroform | $CH\ Cl_3$ | 30 | 100 | |
| Trichlorofluoromethane | $C\ Cl_3\ F$ | | | |
| Tetrachloromethane, carbon tetrachloride | $C\ Cl_4$ | 3 | 5 | |
| Total Halomethanes | | | 100 | |
| ***Ethanes*** | | | | |
| Chloroethane | $CH_3\text{-}CH_2Cl$ | | | |
| Bromoethane | $CH_3\text{-}CH_2Br$ | | | |
| 1,1-Dichloroethane | $CH_3\text{-}CH_2Cl_2$ | | | |
| 1,2-Dichloroethane | $CH_2Cl\text{-}CH_2Cl$ | 10 | 5 | |
| 1,2-Dibromoethane | $CH_2Br\text{-}CH_2Br$ | | | |
| 1,1,1-Trichloroethane | $CH_3\text{-}CCl_3$ | 30 | 200 | |
| 1,1,2-Trichloroethane | $CH_2Cl\text{-}CHCl_2$ | | | 41.8$^{d}$ |
| 1,1,2,2-Tetrachloroethane | $CH\ Cl_2\text{-}CH\ CL_2$ | | | |
| Hexachloroethane | $CCl_3\text{-}CCl_2$ | | | 8.7$^{d}$ |
| ***Ethenes or Ethylenes*** | | | | |
| Chloroethene | $CH_2 = CHCl$ | | | 5$^{e}$ |
| 1,1-Dichloroethene | $CH_2 = CCl_2$ | 0.3 | 7 | |
| cis 1,2-Dichloroethene | $CHCl = CHCl$ | | | |
| trans 1,2-Dichloroethene | $HCl = CHCl$ | | 70 | |
| Trichloroethene | $CCl_2 = CHCl$ | 30 | 5 | |
| Tetrachloroethene | $CCl_2 = CCl_2$ | 10 | 10 | |
| ***Aromatics*** | | | | |
| Benzene | $C_6H_6$ | 10 | | 1$^{c}$ |
| Toluene | $C_6H_5CH_3$ | | 2000 | |
| Ethylbenzene | $C_6H_5(CH_2CH_3)$ | | 680 | 3280$^{d}$ |
| Chlorobenzene | $C_6H_5Cl$ | 0.1 | | 488$^{d}$ |
| o-xylene | $C_6H_4(CH_3)_2$ | | | |
| p-xylene | $C_6H_4(CH_3)_2$ | | | |
| m-xylene | $C_6H_4(CH_3)_2$ | | | |
| Styrene, vinylbenzene | $C_6H_5CH=CH_2$ | | 120 | 931$^{e}$ |
| 1,2-Dichlorobenzene | $C_6H_4Cl_2$ | 0.1 | 750 | |
| 1,3-Dichlorobenzene | $C_6H_4Cl_2$ | | | |

| | | |
|---|---|---|
| 1,4-Dichlorobenzene | $C_6H_4Cl_2$ | $4.7^e$ |
| 1,2,4-Trimethylbenzene | $C_6H_3(CH_3)$ | |
| 1,2,3-Trichlorobenzene | $C_6H_3Cl_3$ | |
| 1,2,4-Trichlorobenzene | $C_6H_3Cl_3$ | |
| 1,3,5-Trichlorobenzene | $C_6H_3Cl_3$ | |
| Naphthalene | $C_{10}H_8$ | $143^d$ |
| Hexachlorobenzene | $C_6Cl_6$ | $0.35^e$ |
| Cumene, methylethylbenzene | $C_6H_5\text{-}CH(CH_3)_2$ | |

a - World Health Organization Guidelines
b - U.S. Environmental Protection Agency, maximum contaminant limit, National Drinking Water Standard
c - Florida Groundwater Consent Decree
d - Oklahoma Guidelines
e - New York State Guidelines

# 2

# TECHNICAL SUMMARY OF SITE STUDIES

## 2.1 Borden Landfill

### 2.1.1 Borden Site Location and Plume Description

The Borden site is an abandoned sanitary landfill situated on an unconfined aquifer of glacio-fluvial sand. It is located within the confines of Canada Forces Base Borden, approximately 80 km NW of Toronto. The inorganic leachate composition, and plume configuration are known in exceptional detail (see Jour. Hydrology, *63*, no. 1-2, 1983). The site, which was operated from 1940-1973, received mainly wood and construction debris (80%). The remainder consisted of domestic and commercial wastes. Refuse was periodically burned.

The sandy water table aquifer is contaminated with the leachate plume extending for 900 m in an upper, unconfined zone. The velocity of the groundwater is estimated to be on the order of 0.1 to 1 m per day.

The extent of the plume as determined from chloride data is depicted in Figure 2.1. Also shown is the area where wastes are buried and the locations of the observation wells sampled for organics. Figure 2.2 shows the distribution of chloride and total volatile halogenated organics (halocarbons) along cross-section AA' indicated in Figure 2.1.

*Figure 2.1*: The extent of the leachate plume at the Borden landfill site and the location of piezometers samples for organic analyses.

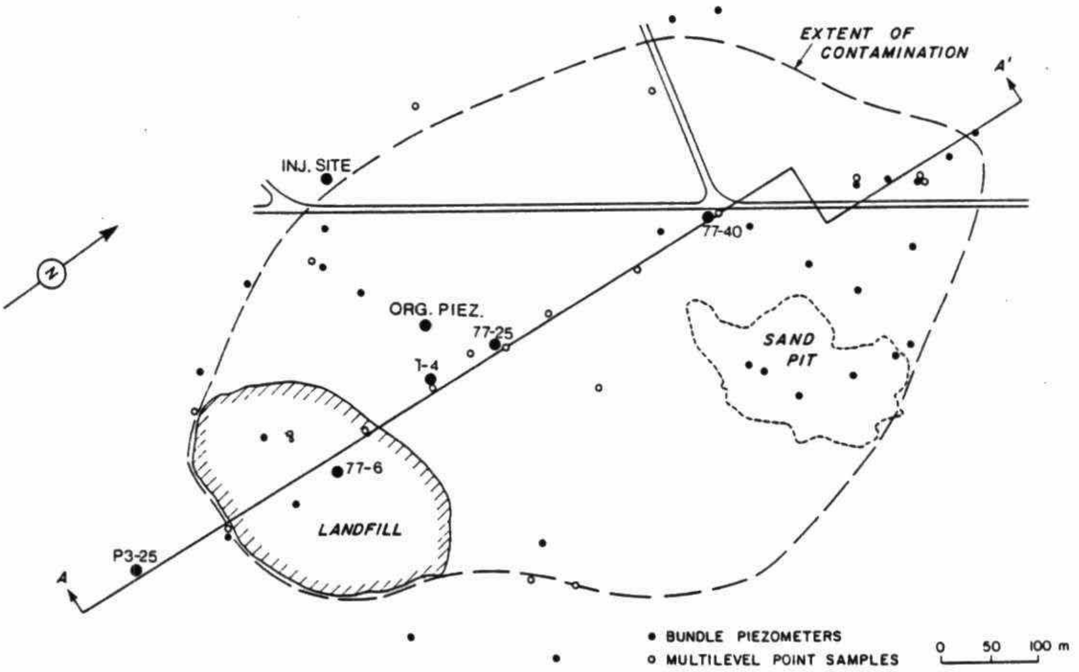
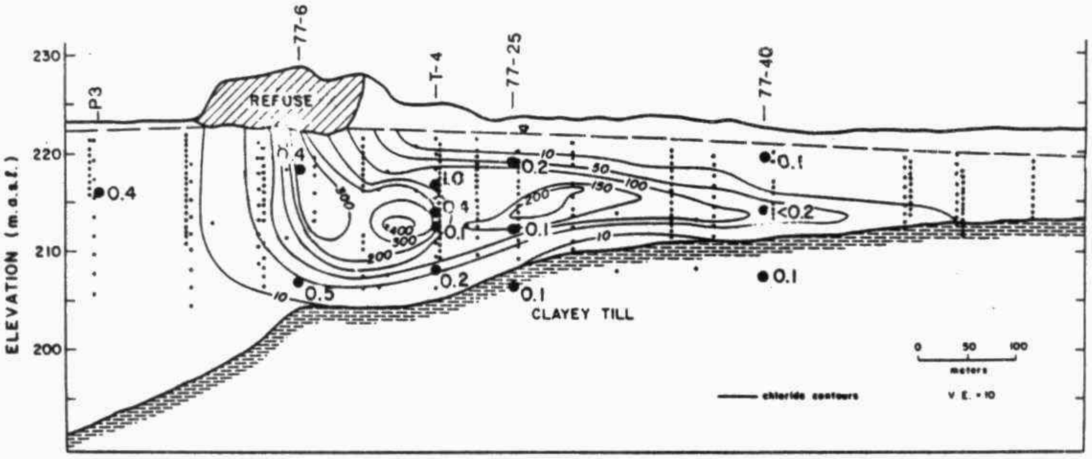


*Figure 2.2:* The distribution of chloride and total halocarbons along cross-section AA' (see Figure 2.1), Borden landfill site.



### 2.1.2 Sampling

Samples were taken in order of increasing concentration to reduce the possibility of cross-contamination. Background samples were taken first, leachate from close to the landfill last. Prior to sampling, 3 to 5 piezometer volumes of wellwater was removed to ensure that the subsequent sample was representative of the groundwater. Teflon tubing was inserted into the piezometer tubes and was connected to a 2 litre flask. The pump was connected after the flask so that the sample came in contact with only Teflon and glass. Two one litre samples were taken at each sampling location for analysis of organic acids, phenols, neutrals (including purgeables), and bases. In addition one or several 50-mL samples were taken for volatile organics analysis. Vials (50-mL) were filled with the content of the Teflon tube removed from the piezometer, thereby using the tube as a bailer. To minimize loss of volatiles during filling, several volumes of sample were displaced before the vial was capped, air-tight and free of head space.

Our experience and that of other suggests that the loss of volatile organics caused by this sampling protocol is less than 10% (Barker et al., 1987; Pankow, 1986 and Patrick et al., 1986).

Where the water table was too deep for sampling by suction, samples were taken by inserted a Teflon tube into the piezometer, applying suction, removing the tube and directing the groundwater into a sampling bottle. Samples tended to develop gas bubbles as they were brought to the surface, which might have caused some loss of volatiles. Again we estimate losses were less than 10% for the organics determined. Between sampling locations, the equipment was rinsed with deionized water and with water to be sampled. Samples were stored under refrigeration until analyzed. Analyses were done usually within a week.

### 2.1.3 Analytical Procedures

The analytical procedures are described by Reinhard et al. (1984). Volatile halogenated $C_1$-$C_2$ organics were analyzed by pentane extraction followed by electron-capture gas chromatography (GC) analysis. Purgeables were analyzed using a closed-loop stripping (CLS) procedure. Heavily contaminated samples were diluted five times with purified water prior to CLS analysis. Base/neutrals and acid/phenols were analyzed using a method similar to EPA method 625 (Fed. Regist. 1976, *44* (233), 69540-694552) modified as follows. Two-litre continuous extractors were used for the methylene chloride extraction. Base neutrals were extracted at pH 11, acid/phenols were extracted subsequently at pH 2. The acid/phenol extracts were methylated with an excess of diazomethane to improve GC separation. A fused silica (J & W Scientific, Ca) SE-52 capillary column (50 m, 0.3 mm i.d., 0.25 mm film thickness) was used for gas chromatography - mass spectrometry (GC/MS) analysis. Tracor and Carlo Erba gas chromatographs and a Finnigan GC/MS (model 4000) were used for analyses. Concentrations were estimated based on the peak height relative to the peak height of the internal standard using the most intense ions. The concentrations given were not corrected for differences in extraction efficiencies and differences in the detector sensitivities. These corrections might change the absolute concentrations given by more than an order of magnitude. Nevertheless, in the absence of such corrections, comparisons of values from different locations are possible.

### 2.1.4 Results

Table 2.1 summarizes the organics detected in the plume. Of the volatile halogenated compounds only carbon tetrachloride and trichloroethylene were present in concentrations above trace levels but their presence did not seem to be related to the presence of leachate (Figure 2.2). Background values measured at P3-25 were not significantly different from concentrations measured in samples from within the plume.

Detailed characterization by GC/MS using closed-loop stripping and methylene chloride extraction seemed to indicate that relatively few compounds of industrial origin were buried Those identified were present at levels close to the background values found at P3-25 (Table 2.1). Di-ethyl-phthalate was measured in all wells tested. Because phthalic acid esters are ubiquitous, trace concentrations are difficult to interpret. Thus these data are suspect. Triphenylphosphate, which is a fire retardant, was found in the background sample at a level similar to those at 77-25. Thus it is difficult to evaluate the source of this compound. Benzothiazole was found in only one well. The presence of elemental sulfur is interesting; it is known to participate in redox reactions. Assuming pH 6.5 and equilibrium conditions, a pE value of about -2 can be inferred from the presence of sulphur. This is consistent with the reduced conditions observed within the plume. The fatty acids palmitic, stearic, and linoleic are present in living cells and are found widely in the environment. Their estimated concentrations do not indicate a significant contamination by the leachate. Conspicuous is the absence of large amounts of short-chain fatty acids which are formed as by-products of anaerobic degradation. These could have been consumed by methanogenic bacteria in the landfill itself.

The aromatic hydrocarbons detected are components of gasoline and other petroleum products. Some are used as solvents and intermediates. The concentrations observed within the plume are generally very low and close to the detection limit. Generally, a significant contamination of the groundwater by organics is not evident.

### 2.1.5 Conclusions

Organic contaminants are not significant in the leachate plume emanating for the non-abandoned landfill site. This probably reflects the nature of the bulk of the landfill material - wood and construction debris, and the burning of the domestic and commercial wastes.

Most of the organic compounds identified at ug $L^{-1}$ levels could have come from leaching of piezometer material (PVC, teflon and polyethylene tubing) or were present in background groundwater.

Given the general lack of organics in the leachate plume, it is not possible to derive information concerning the mobility or persistence of organic contaminants at this landfill site.

*Table 2.1*: Borden Landfill Leachate Plume Organics Tentatively Identified by GC/MS

***Volatiles***

Acetone*
Methylene chloride*
Ethyl Acetate*
Tetrahydrafuran**
2-Pentanone, 4-methyl**
Hexamethyl cyclohexasiloxane**
Octa methyl cyclohex siloxane**
Dichlorobenzene**
Chloroform*
Carbon tetrachloride (0.1)
Trichloroethylene (1)
Benzene (3)
Toluene* (1)
Ethylbenzene (0.3)
Anthracene* (0.3)

***Acids***

Palmitic (13)
Stearic 1(6)
Linoleate (3)

***Miscellaneous***

Triphenylphosphate* (0.4)
Di-ethyl-phthalate (12)*
Benzothiazole (0.7)
Sulphur (S8) (>100)

* also identified in background groundwater from P3-25
** reported or suspected solvent for PVC, PVC glue or silicone lubricant
approximate maximum concentrations (ug L$^{-1}$) are in brackets where estimated

## 2.2 Woolwich

### 2.2.1 Site Hydrogeology

The Woolwich landfill is located in the northwestern part of the Regional Municipality of Waterloo, Ontario (Figure 2.3). It is situated on a deposit of glaciofluvial sand which is generally about 30 m thick and rests on a deposit of relatively impervious clayey till. The landfill occupies approximately 3.5 hectares, of which 75% have been filled. Operation began in the mid-1960s. The site received rural, municipal, and some industrial wastes from a nearby tire manufacturer. The landfill is covered with sand only. Rain and snow melts infiltrate the refuse and after migration through the unsaturated zone disperse into the underlying ground water 10 to 15 m below. The monitoring network included 72 bundle piezometers, each having eight to nine individual piezometers at different depths between the water table and the bottom of the water table aquifer.

A novel method was developed to collect continuous cores of the aquifer material (Appendix A, Zapico thesis). In 1984/85, essentially continuous cores were collected from five locations in the leachate plume: near ML4, near ML19, near ML25, near ML52 and near ML69 (Figure 2.3). Permeameter studies and grain-size analyses were employed on 5 cm sections of the core in order to establish the vertical distribution of hydraulic conductivity (K) of the sandy aquifer material. Figure 2.4 illustrates the results for cored borehole C-1 near ML4. This core has perhaps the least variability in hydraulic conductivity. In general, the hydraulic conductivity decreases with depth. Maximum K values are on the order of $10^{-2}$ cm $s^{-1}$ and minimum K values are on the order of $10^{-5}$ cm $s^{-1}$.

Combining this information with the measured water table gradient (I) (0.0079 to 0.0223) and an assumed porosity of 0.35 via the modified Darcy equation,

$$\bar{v} = -\frac{kI}{n}$$

*Figure 2.3*: The location of the Woolwich landfill site and the extent of the landfill leachate plume.

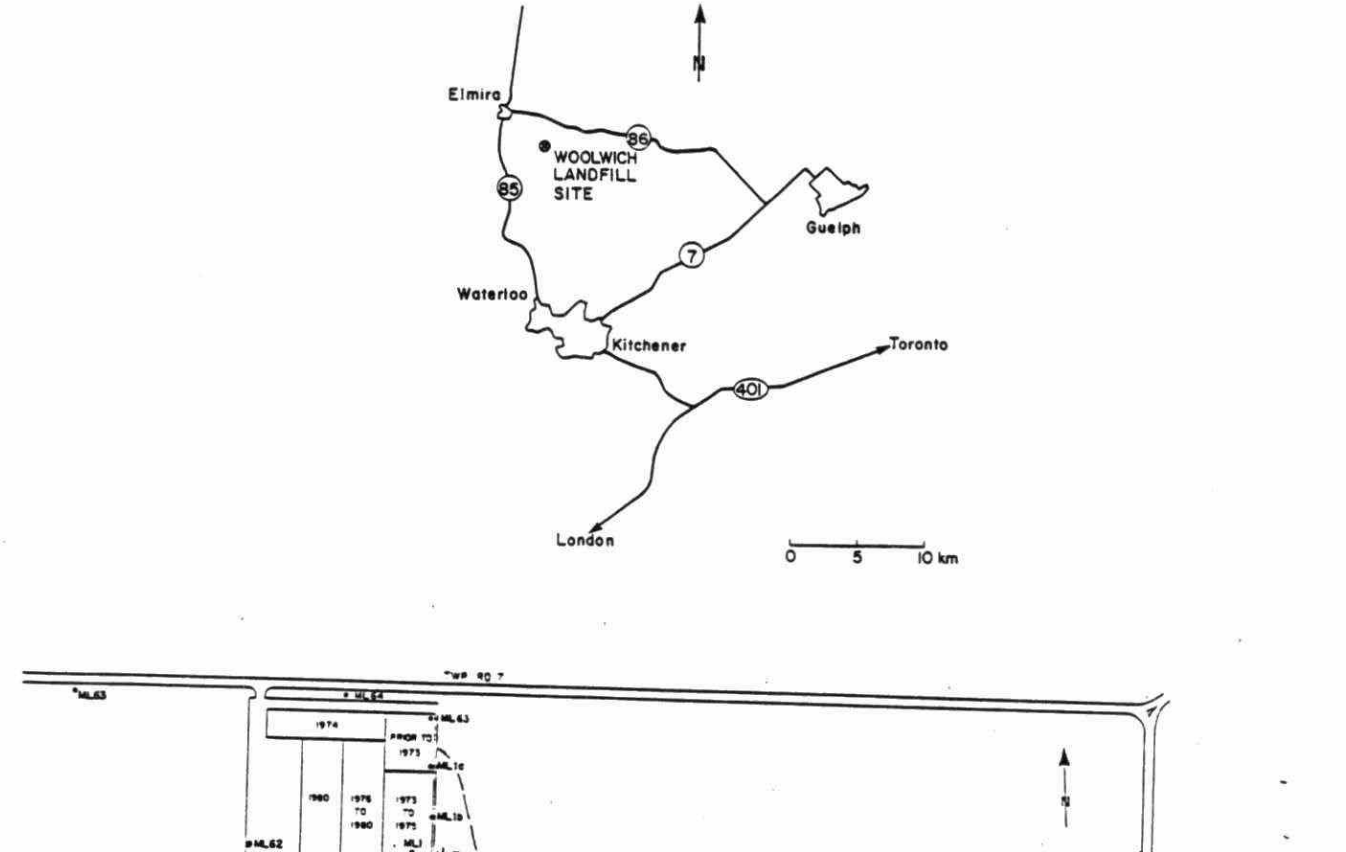
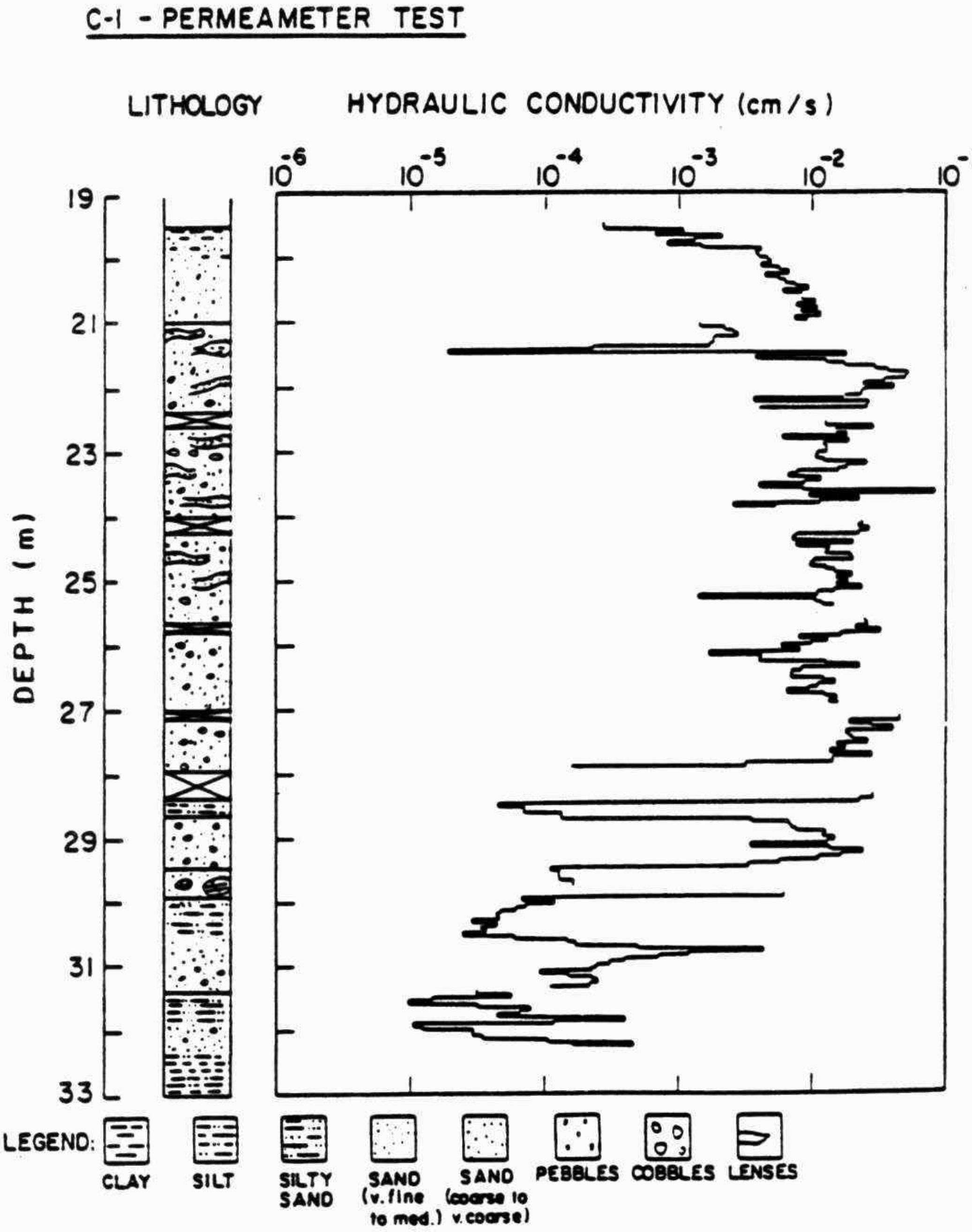


*Figure 2.4*: The lithology and the vertical distribution of hydraulic conductivity at cored borehole C-1, Woolwich landfill site



yields an average linear lateral groundwater velocity ( $\bar{v}$ ) of between about 70 and 200 m $a^{-1}$. This range must be viewed with caution, given the heterogeneous nature of the materials and the fluctuating water table.

The lateral extent of the leachate plume as interpreted from the distribution of chloride in groundwaters in the summer of 1985 is shown in Figure 2.3. The plume appears to extend 900 to 1100 m laterally from the landfill site. Since the landfill was established in about 1967, this indicates that leachate may have migrated at least 900 m in 18 years or with an average linear lateral velocity of at least 50 m $a^{-1}$. This is somewhat lower than the velocity calculated with the Darcy equation. In addition, it may have taken some time for leachate to have been generated in quantities sufficient to penetrate the unsaturated zone beneath the landfilled material. If this was allotted a 2 year period, the front of the plume would have been extended at a higher velocity - at least 56 m $a^{-1}$. This is still somewhat slower than expected. This slower progress of the leachate plume (compared to the range of calculated migration rates) could reflect even longer time was required for breaching the unsaturated zone.

### 2.2.2 Sampling

At Woolwich, the water table was too deep for sampling by suction lift except in the distal segments of the plume. In addition, almost all monitoring wells consisted of bundle piezometers (Cherry et al., 1983) with each of the 8 or 9 depth-specific sampling wells consisting of 1 cm or 1.3 cm diameter polyethylene or PVC tubes of various lengths with the lower 10 to 20 cm slotted and wrapped with Nytex screen. These narrow diameter wells could only be sampled effectively with a gas-drive triple-tube sampler (Robin et al., 1982). The sampler is constructed of Teflon and stainless steel and only a short (5 cm) length of latex tubing. Laboratory studies revealed that this sampling methodology introduced a bias of less than -15% for volatile organics of interest. (Barker et al., 1987).

The shallow water table wells were sampled with teflon tubing and a peristaltic (suction lift) pump as described in Appendix A (K. Ross report 1).

### 2.2.3 Analyses

Initial samples were analyzed by the methods described in section 2.1.3 at Stanford University by Dr. M. Reinhard and his staff. Subsequent analyses at Waterloo for volatile halocarbons utilized similar GC and GC/MS techniques (see Appendix E). Subsequent analyses for volatile aromatic hydrocarbons utilized a similar solvent-extraction technique described by Patrick et al. (1985). These methods and their quality assurance data is described in Appendix E. The bias introduced during sampling is less than -20% and generally less than -10% (Barker et al., 1987).

### 2.2.4 Results

The results of the Stanford analyses were presented by Reinhard et al. (1984). Table 2.2 summarizes the organic contaminants tentatively identified in leachate-impacted groundwaters collected from shallow groundwaters near the site boundary. Data is from multilevel piezometer point ML-4-5 (Reinhard et al., 1984) and more recently from point ML-5-6 (27/11/85). Results from additional piezometers are presented in Appendix A-3.

The organics reported in Table 2.2 are common in sanitary landfill leachates. The most abundant organics are fatty acids and aromatic acids probably produced by anaerobic breakdown of landfill organic matter. Other typical breakdown products include phenolics, aromatic hydrocarbons, and camphor.

Many of the organics present *could* have an industrial origin. They could have been part of the industrial waste landfilled before the site was controlled or they could have been introduced with domestic garbage. Included in this group are the volatile halocarbons (common solvents, cleaners) and volatile aromatics (toluene is a common solvent for example). It is suspected that the alkyl phosphates and nitrogen-containing compounds (benzonitrile, aniline, etc.) originated from tire manufacturing wastes (Reinhard et al., 1984).

The distribution of selected organics in the leachate plume has been monitored since 1982. The emphasis has been upon the volatile halocarbons and volatile aromatics. The location of multilevel piezometers used in these studies and of cross-sections discussed below are shown in Figure 2.3.

Figure 2.3 also indicates the lateral extent of the leachate plume as defined by at least one sampling point containing a chloride concentration above background (19 mg $L^{-1}$, K. Ross, Appendix A-2).

The spatial distribution of contaminants emanating from the landfill is very irregular. Figure 2.5 presents the distribution of chloride, toluene, ethylbenzene, trichloroethylene and 1,1,1-trichloroethane in the vertical cross-section AA' (see Figure 2.3). The highest concentrations usually occurred at shallow in intermediate depths. The highest aromatic concentrations occur at piezometers ML-04, 04A and 04B, while the highest halocarbon concentrations also occur at ML 07 and 06. This area is immediately down-gradient from one of the oldest cells of the landfill (see Figure 2.3). The general lack of such high level of contaminants adjacent to newer landfill areas reflects the delay of significant groundwater contamination for some period of time, perhaps due to slow leaching of fill and slow transport through the unsaturated zone.

One aspect of contaminant occurrence along AA' addressed in Appendix A-2 is the inter-correlation of indicator parameter (TOC, Cl) concentrations and trace organic concentrations. The computed correlation coefficient for Cl and TOC is good (0.873), but the coefficients for Cl with 14 volatile trace organics (halocarbons and aromatics) are poor, ranging from -0.37 to 0.678. Correlations within the aromatic hydrocarbons were generally quite good, suggesting they have a common source and little difference

*Figure 2.5*: The distribution of contaminants in the vertical cross-section AA', adjacent to the Woolwich landfill site (see Figure 2.3)

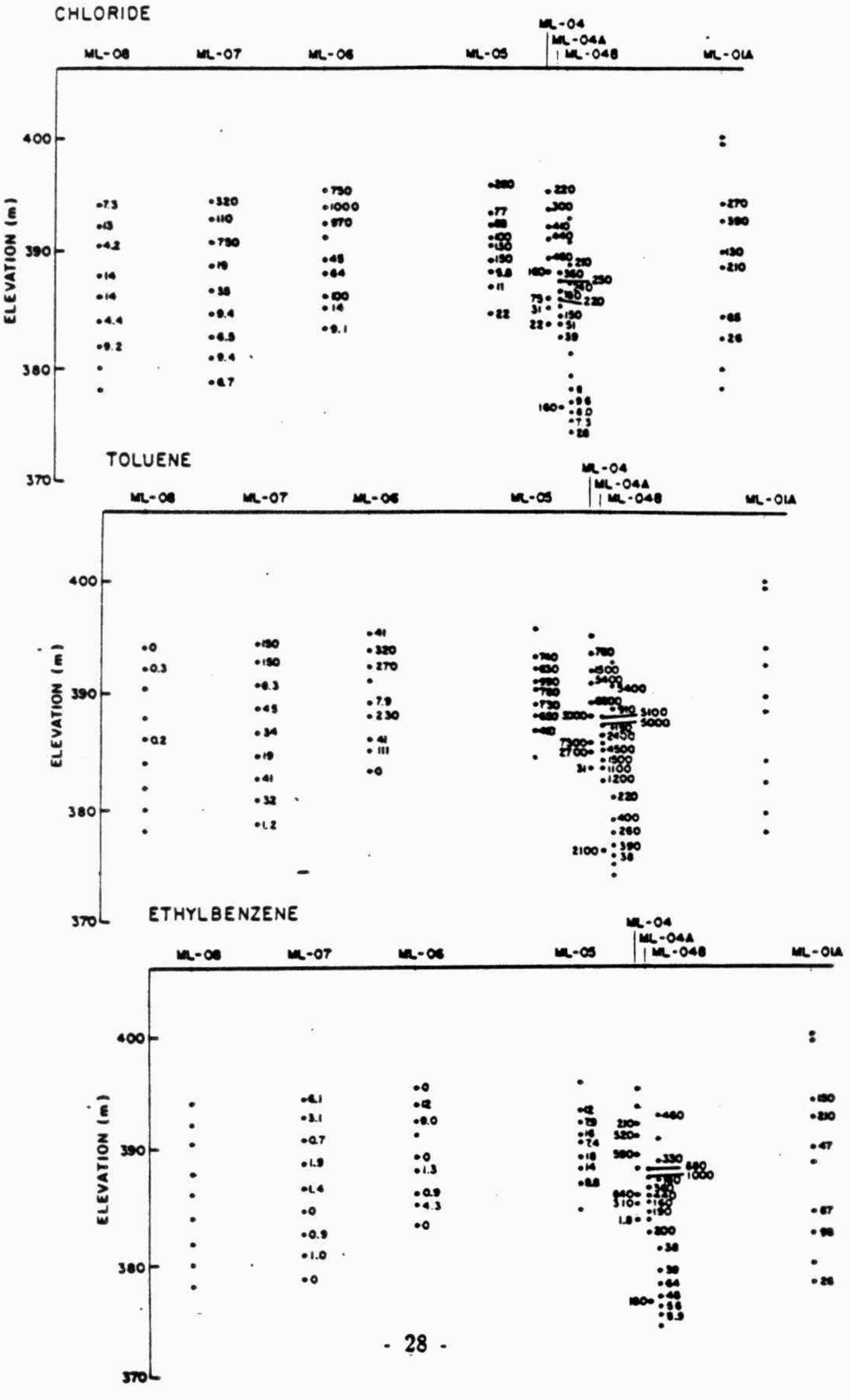
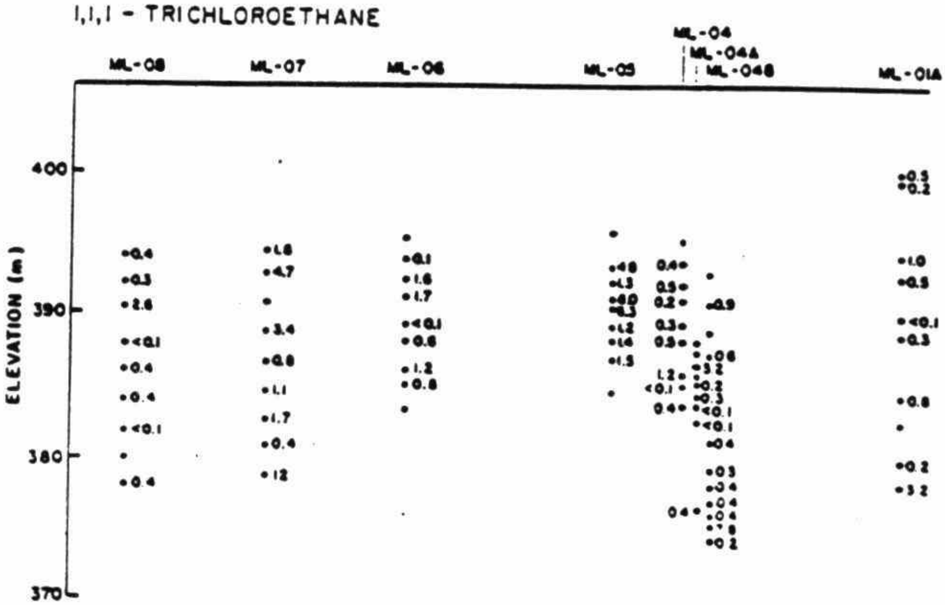
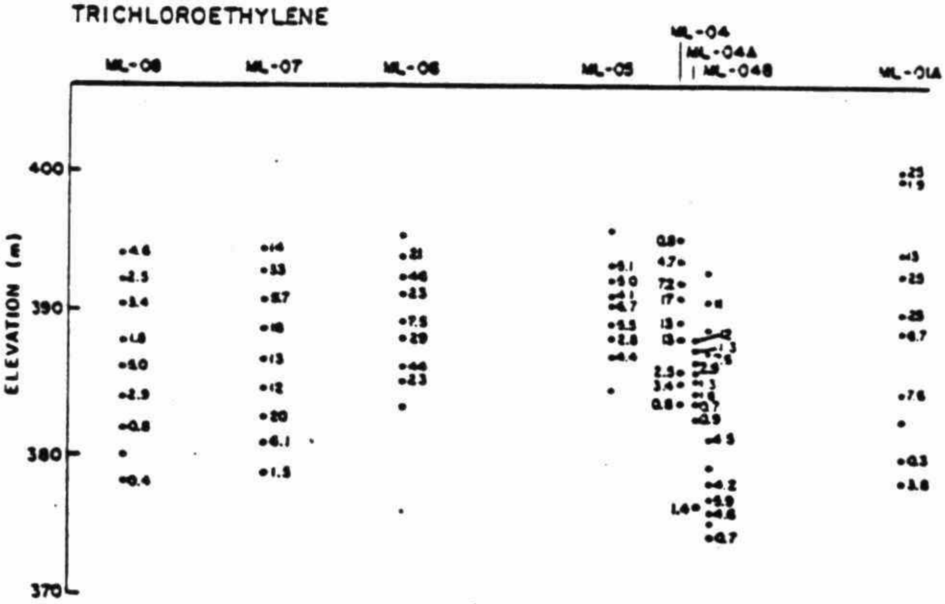


Figure 2.5 cont'd.





in migration and persistence at least near the landfill. The halocarbons were generally at much lower concentrations. They were poorly correlated with other halocarbons, with indicator parameters and with aromatic hydrocarbons. This could reflect more variable sources of halocarbons with unrelated sources of individual compounds. It could also reflect reactions within the landfill which preferentially reduce the concentrations of only certain compounds.

The spatial distributions of Cl, methane ($CH_4$), dissolved oxygen ($O_2$,) trichloroethylene (TCEY) and 1,1,1-trichloroethane (TCEA) along cross-section BB' (Figure 2.3) are shown in Figure 2.6. This cross-section was close to the core of the contaminant plume emanating from this site (Zapico thesis, Appendix A-1). However, part of the irregular Cl distribution in a lateral sense could be due to the selection of some piezometers (16, 19, 21, 25) that are laterally removed from the plume core where concentrations are expected to be highest.

The chloride distribution in Figure 2.6a shows the significant concentration declines away from the source. This is commonly observed in landfill leachate plumes. Near the landfill, Cl concentration in excess of 200 mg $L^{-1}$ are common, whereas 900 to 1000 m from the landfill concentrations do not exceed 50 mg $L^{-1}$. The low concentrations ($< 50$ mg $L^{-1}$) in the central part of cross-section BB' (piezometers 16 to 25) probably reflect the off-centre location of these piezometers. An additional near-surface Cl source is possible for $> 50$ mg $L^{-1}$ values observed at shallow depths in piezometers 52 and 58.

Methane was only found in piezometers near the landfill (Figure 2.6b). In these piezometers, oxygen was not detected (Figure 2.6b), confirming the anaerobic, extremely-reducing, conditions in the plume near the landfill. At depth in piezometer 4b and beyond the edge of the landfill, no methane and measurable oxygen levels were found in the groundwater. This indicates that the plume has become aerobic,

*Figure 2.6:* The distribution of contaminants in the vertical cross-section BB' at the Woolwich landfill site (see Figure 2.3).

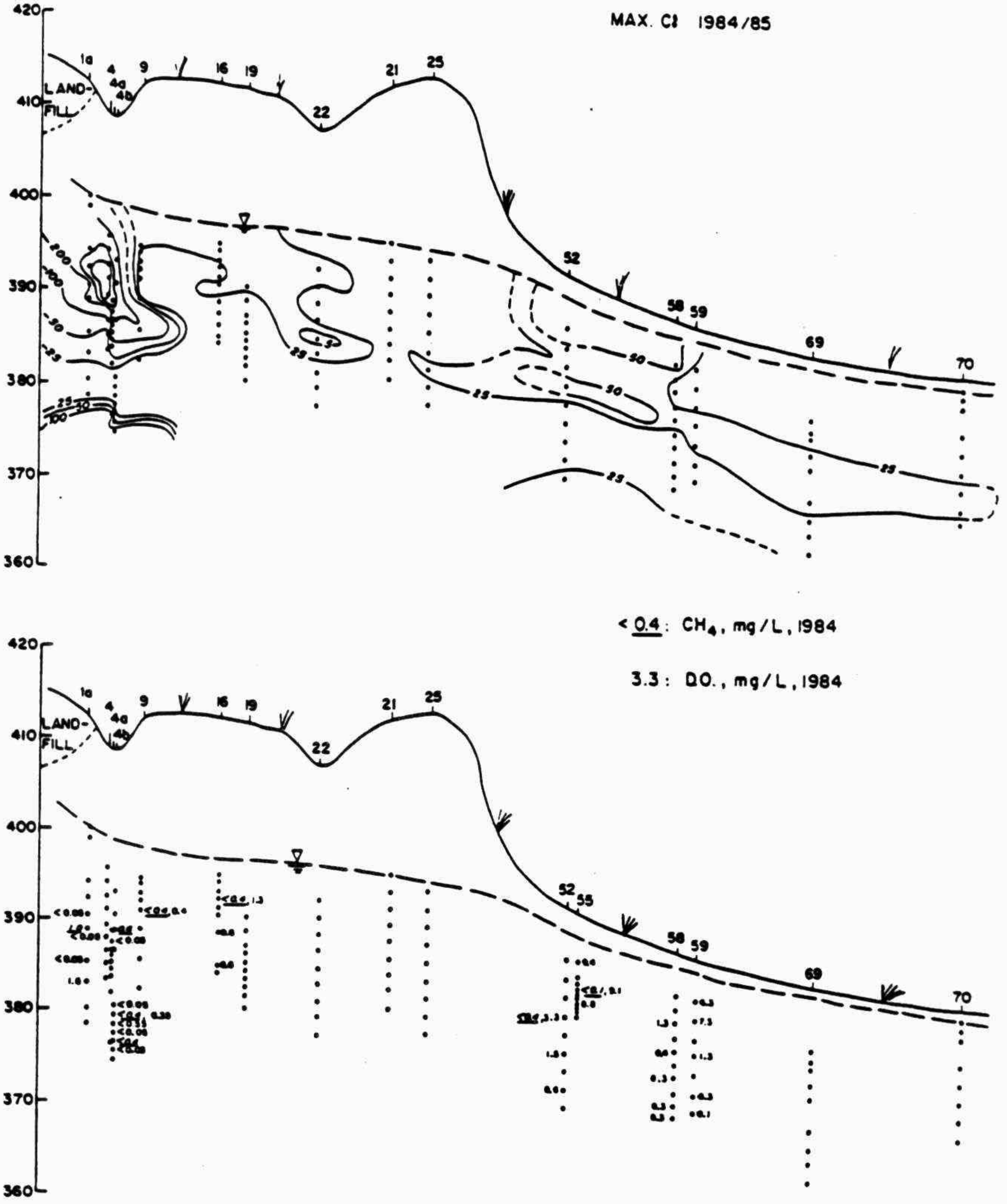
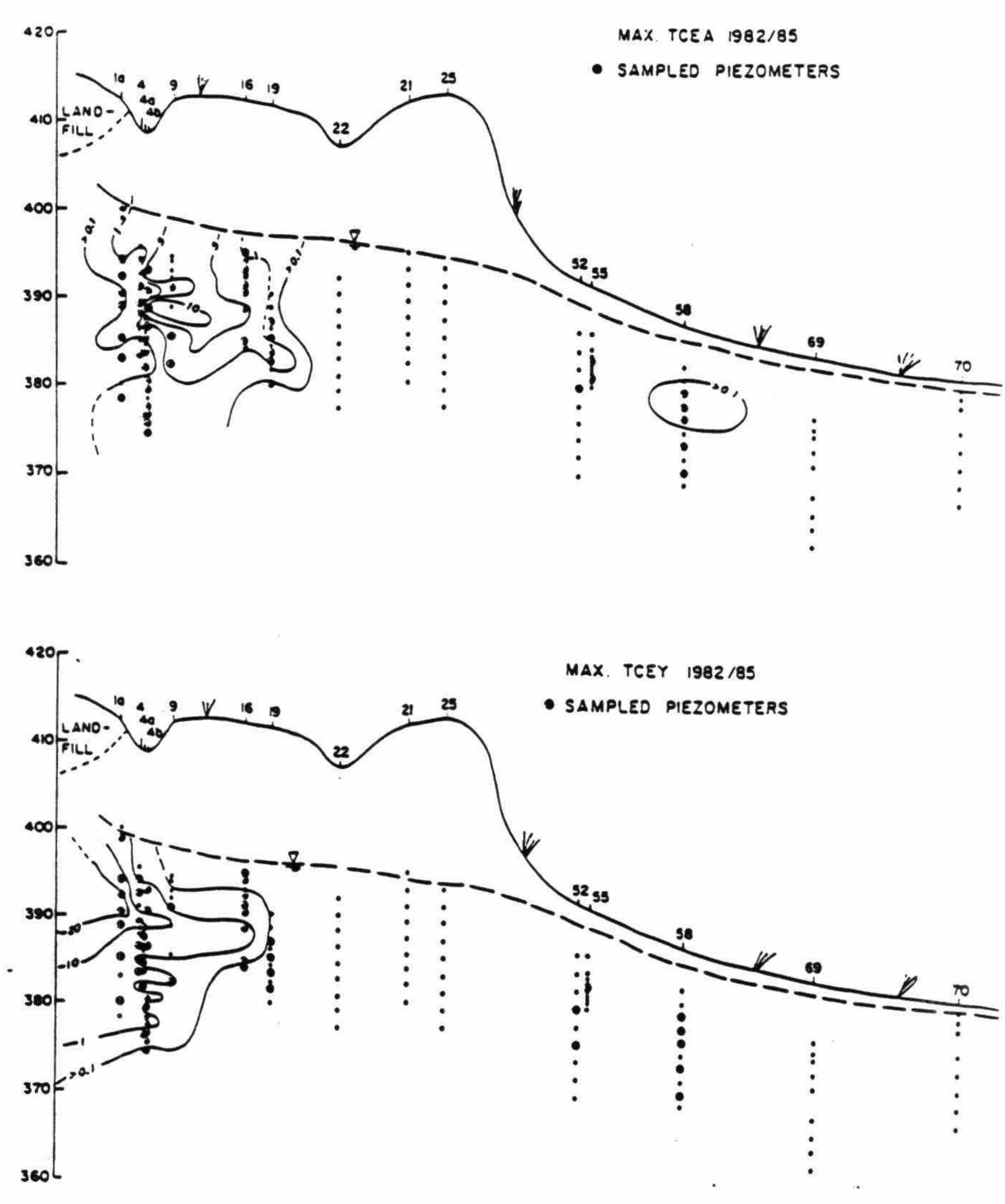


Figure 2.6 cont'd.



probably within 150 m of the landfill. Oxygen is presumably introduced by dispersion whereby uncontaminated waters are mixed with leachate during migration of the contaminants.

The generally low concentrations of halocarbons along cross-section AA' (Figure 2.6c,d) could indicate that 1) they are not present in the landfilled material 2) they are not leached significantly, 3) they do not survive transport through the unsaturated zone or 4) they do not survive transport through the saturated zone. Removal mechanisms should be evaluated to evaluate these possibilities.

Assuming that halocarbons are all present in the landfill, they should be leachable, having water solubilities in excess of 200 mg $L^{-1}$. Because they are volatile, they could be lost to the soil atmosphere during migration through the unsaturated zone. Such loss should influence the most-volatile organics to the greatest extent. The most volatile halocarbon, trichloroethane, was found at about the lowest concentration. The halocarbons founds at the highest concentration, trichloroethylene and chloroform, are the least volatile compounds. Thus loss in the unsaturated zone could be significant in producing the halocarbon distributions.

During transport in the unsaturated zone, the environment could be aerobic, but given the tendency of landfills to produce anoxic conditions, oxygen is very likely not significant in the unsaturated zone beneath the landfill. Low levels (0.4 to 1 mg $L^{-1)}$ of methane but no oxygen were commonly detected in highly contaminated wells suggesting that the leachate plume remained strongly anaerobic at least where organic loading from the landfill was high. Thus, it is assumed that halocarbons are migrating in an essentially anoxic and strongly reducing environment. Under such conditions methanogenic bacteria may be active. These bacteria have been shown to dechlorinated 1- and 2- carbon compounds (Vogel and McCarty, 1985; Bouwer and McCarty, 1983). Tetrachloroethylene has been shown to degrade to trichloroethylene and this might account for the lack of the former and the significant levels of the latter in groundwaters at the Woolwich site. In general, the irregular distribution of low concentrations of halocarbons compared to other contaminants and chloride could be due to an irregular distribution of methanogenic activity causing erratic halocarbon removal by biodegradation.

The generally higher levels of aromatic hydrocarbons and their higher internal correlation of concentrations is consistent with a steady source in the landfill and a general lack of selective biodegradation. Most aromatics are readily biodegraded under aerobic conditions (Patrick et al., 1985) but are much more recalcitrant under anaerobic conditions (Barker et al., 1987), even though slow biodegradation has been indicated under extremely reducing, methanogenic conditions (Barker et al., 1986; Wilson et al., 1986). The persistence of aromatic hydrocarbons in the landfill vicinity indicates that anaerobic conditions dominate in this part of the leachate plume. The apparently high input of fatty acids (Table 2.2) commonly found only in anaerobic systems, supports this conclusion. Whereas halocarbons are expected to undergo biodegradation in the vicinity of the landfill, aromatic hydrocarbons are not.

TCEA and TCEY occur at significant levels only in groundwaters within 150 m of the landfill (Figure 2.6c,d). Dispersion could be the cause of much of the concentration reduction apparent over the total leachate plume. However, if the four-fold dilution observed for Cl over 800 m transport represents dispersive dilution, then TECY concentrations of > 10 ug $L^{-1}$ near the landfill should only be reduced to about 2-3 ug $L^{-1}$ at piezometers 52, 55, 58, 69 and 70. In fact, the concentrations appear to be reduced to < 0.1 ug $L^{-1}$. Other attenuation mechanisms seem to be operating. Sorptive retardation is expected to be slight, given the low organic carbon content of the sand/gravel aquifer (0.02% organic carbon (OC)). Theoretical predictions (Barker, 1987) suggest that TCEY and TCEA should move at about 75 to 80% of the groundwater and Cl velocity. Since Cl has reached piezometers 69 and 70, TCEY and TCEA should have reached piezometers 52 and 58. Since they have not, an additional attenuation process is probably operating.

Given the anaerobic, perhaps methanogenic aquifer conditions near the landfill, it seems likely that considerable TCEY and TCEA concentration reductions could occur via biodegradation. Given the extent of concentration reductions observed in the plume and the apparent inability to account for these reductions through dispersive dilution or sorptive retardation, anaerobic biodegradation is considered likely.

Away from the landfill, the aerobic conditions of the leachate plume should promote aerobic biotransformations of most of the aromatic hydrocarbons found in high concentration at piezometers 1a, 4, 4a, 4b and 5 in cross-section AA' (Ross report; Appendix A). These compounds were not detected in piezometers beyond 500 m of the landfill although very few piezometers were evaluated for these compounds. As wth TCEA or TCEY, dispersive dilution and sorptive retardation do not seem to account for the restricted distribution of the aromatics (essentially undetected in piezometers 52, 55, 56) and so biodegradation must also be included to account for their attenuation.

### 2.2.5 Conclusions

A leachate plume emanating from the Woolwich landfill extends for more than 1000 m in the unconfined, sandy aquifer. Significant concentrations of organic contaminants are restricted to within about 100 m for the landfill site. Dispersive dilution and probably biodegradation are limiting the migration of significant concentration of volatile aromatic and chlorinated hydrocarbons.

*Table 2.2:* Woolwich Landfill Leachate Plume Organics Tentatively Identified by GC/MS

***Volatiles***

1,1,1-trichloroethane (7)
trichloroethylene (37)
tetrachloroethylene (2)
chloroform (20)
carbon tetrachloride (5)

benzene (70)
toluene (7500)
p/m-xylene (470)
o-xylene (250)
ethylbenzene (1050)
chlorobenzene (6)
cumene (15)
1,2,4-trimethylbenzene (3)
naphthalene (52)

***Phenols and Acids***

phenol (460)
methylphenol isomers (610)
ethylphenol isomers (17)
chlorocresol isomers (14)
benzoic acid (> 1000)

methylbenzoic isomer (> 1000)

dimethylbenzoic isomer (> 1000)

benzeneacetic acid
phenylacetic acid (>10,000)
3-phenylpropanoic acid (> 10,000)
4-phenyl butonic acid (10)
benzenedicarboxylic
acid isomer (70)
dichlorohydroxybenzoic
acid (trace)
various $C_5$ to $C_{18+}$
fatty acids (> 1000)

***Base/Neutrals***

5-methyl-2-hexanone
2-hexanol

methyl esters of various
fatty acids
tributyl and triethyl
phosphate (17)
diethylester of phosphoric
acid
cyclohexanemethanol

camphor

benzonitrile (30)
methylbenzo nitrite
isomer (10)
aniline (10)

tetramethylthiurea (20)

benzamide derivative
cyanobenzoic acid isomer
(34)

bracketed values are approximate concentrations in ug $L^{-1}$.

## 2.3 The North Bay Landfill Leachate Plume

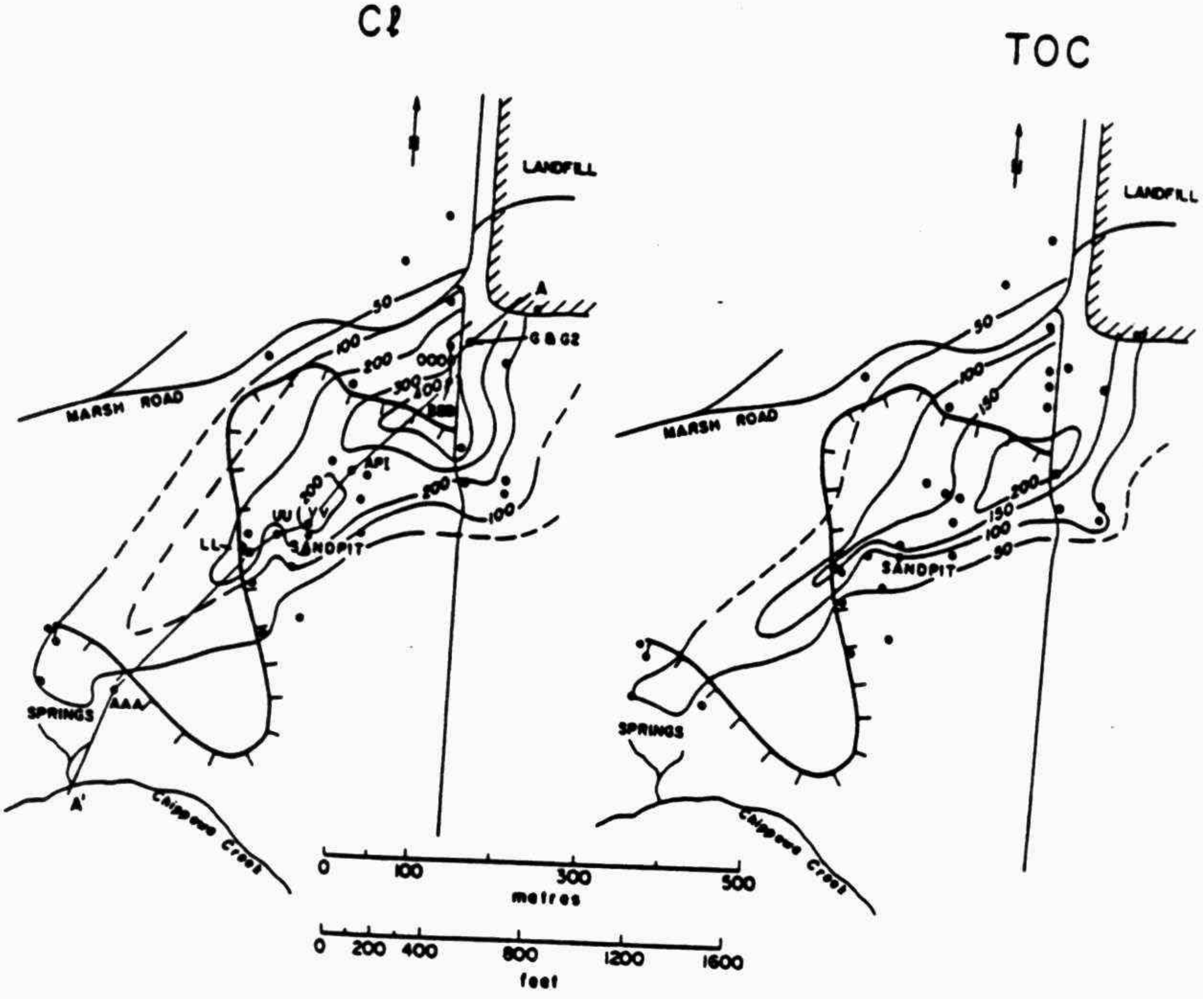
### 2.3.1 Site Hydrogeology

The most intensively studied landfill site is at North Bay, Ontario (Reinhard et al., 1984; Barker et al., 1986). The landfill lies in a complex deposit of bedded glaciofluvial sands underlain by gneissic bedrock. The site has operated since 1962 and leachate-contaminated groundwater has been observed discharging near a creek, about eight hundred meters from the landfill, since our studies began in 1980. Thus, at this site we have not been able to discuss a plume front, as is found at the other sites. Mobile contaminants have reached the discharge zone, albeit at very low concentrations. This study, therefore, cannot deal with relative velocities of contaminants, but rather provides field evidence of contaminant transformation and persistence during transport in anoxic groundwater.

Recent hydrogeological studies (M. Moore, M.Sc. thesis, Appendix B) have identified a relatively thick sand of rather uniform appearance and hydraulic conductivity (about $1x10^{-2}$ cm $s^{-1}$) probably extending throughout the flow system. Average lateral groundwater velocities appear to be from $4x10^{-4}$ cm $s^{-1}$ to $1x10^{-3}$ cm $s^{-1}$. Unretarded contaminants could, therefore, be moving through the flow system within two to four years.

The plume does not show significant lateral spreading (Figure 2.7). This is unusual, especially compared to the well-studied Borden plume (Figure 2.1) and could represent the occurrence of a bedrock depression which limits the plumes lateral extent (see Appendix B-2).

*Figure 2.7*: The areal distribution of maximum concentrations of chloride and total organic carbon (TOC) in groundwaters from multilevel piezometers at the North Bay landfill site.



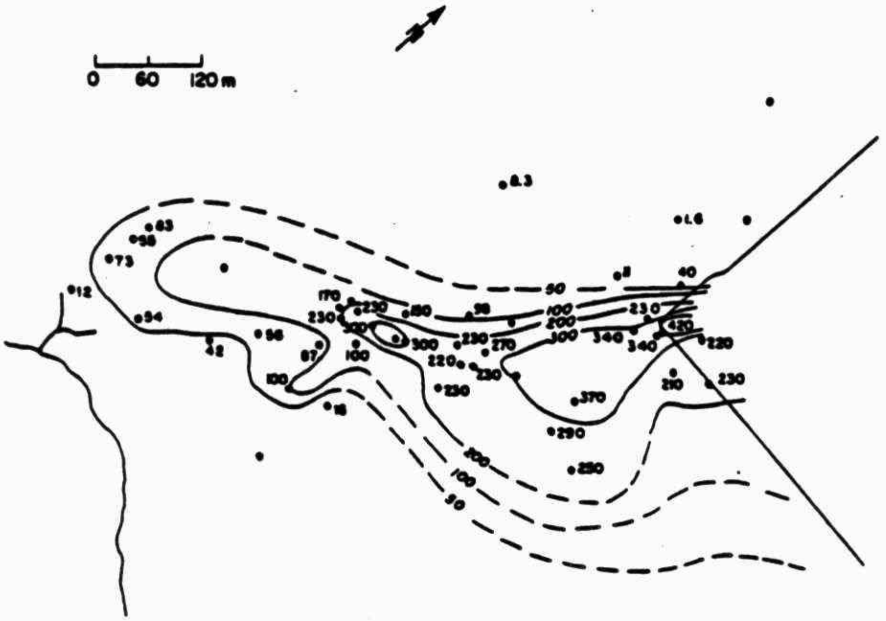
### 2.3.2 Organic Contaminants

The sampling, analyses and organic geochemistry of the leachate is discussed by Reinhard et al. (1984), Barker (in press), Barker and Cherry (1986), Barker et al., (1985) and Barker et al. (1986). Figure 2.7 shows the plan view of the leachate plume defined by Cl and TOC concentrations and the location of piezometers used to construct cross-sections. Tables 2.3 and 2.4 presents the geochemistry of groundwaters along the plume for 1983-1984. Figure 2.8 show the plan view of the maximum contaminant concentrations at each multilevel piezometer. Figure 2.9 shows the distribution of the indicator parameter chloride (Cl) and selected aromatic hydrocarbons in the vertical cross-section along the centre of the leachate plume. Volatile halocarbons do not persist beyond about 200 m in this plume, probably due to their biotransformation under the methanogenic conditions of this plume (Reinhard et al., 1984). Volatile aromatics are more persistent, however, and are found occasionally in the discharge zone, although at significant attenuation. Considerable dilution due to dispersion is evident in the declining concentrations along the plume of rather unreactive constituents such as Cl, Na, K, Ca and Mg.

Spatial and temporal variability of contaminant distributions have been the focus of recent studies (Barker et al., 1985). Although there has been considerable fluctuation in the concentration of the indicator parameters chloride (Cl) and dissolved or total organic carbon (DOC of TOC) at particular points, their overall distribution is rather constant. The general distribution of organic contaminants is similar to chloride (Figure 2.8b to i). Sampling during 1985 on a monthly basis revealed considerable temporal variation in the indicator parameters and aromatic hydrocarbons at individual points (Figure 2.10). This variability may be seasonal, but further data assessment is required to evaluate the seasonality.

*Figure 2.8*: The areal distribution of maximum concentration of various contaminants at the North Bay landfill site.

CHLORIDE, JULY 85



BENZENE, JULY 85

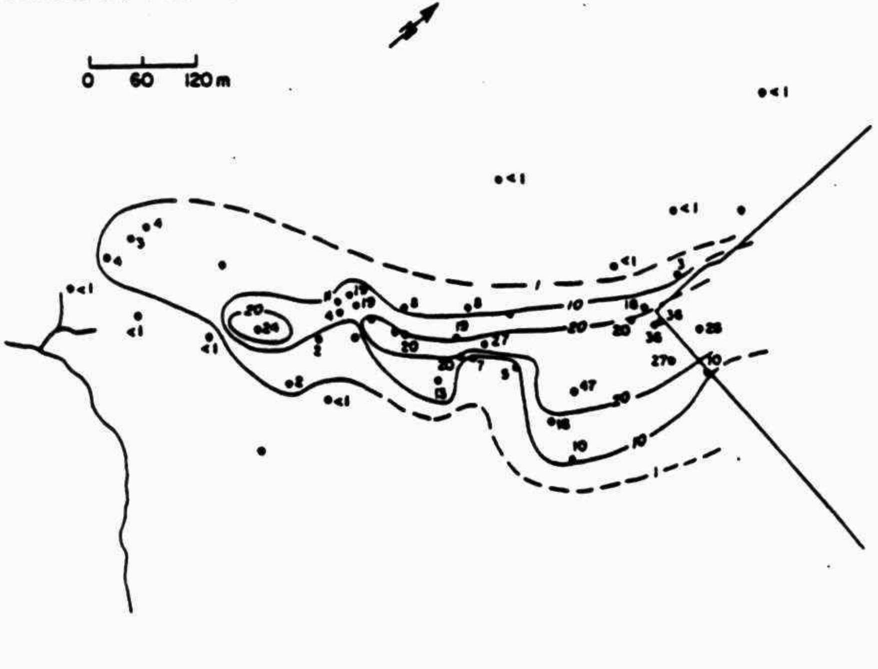
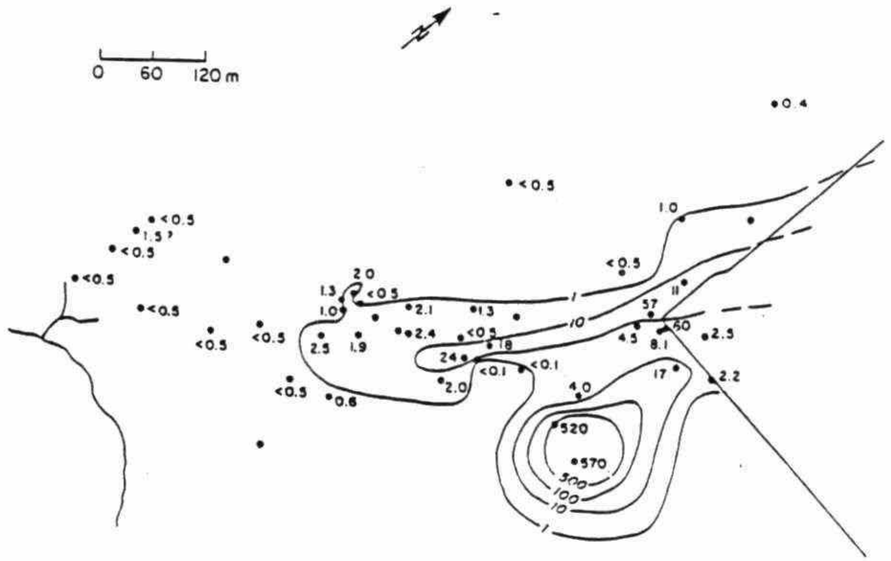
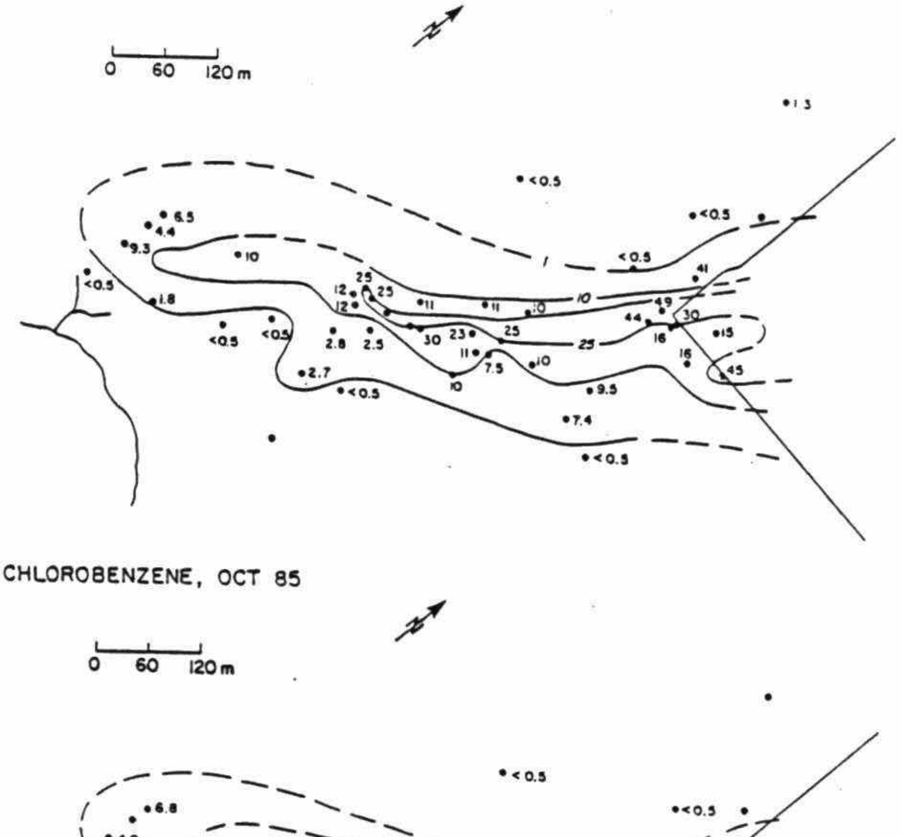


Figure 2.8 cont'd.

TOLUENE, JULY 85



CHLOROBENZENE, JULY 85



CHLOROBENZENE, OCT 85

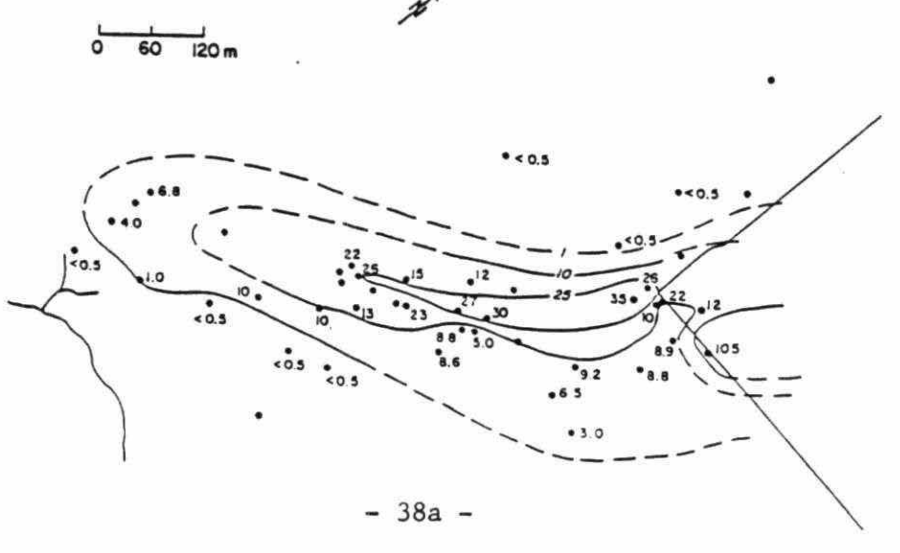
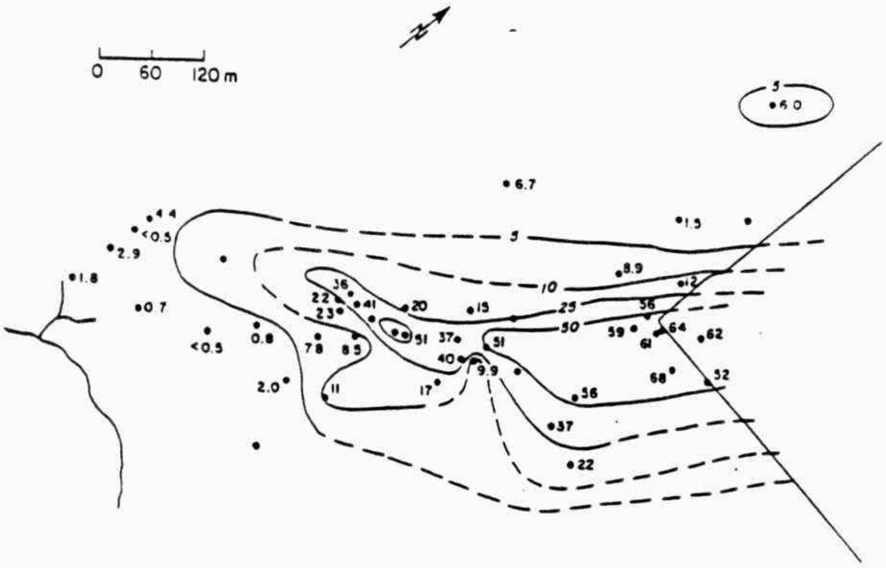
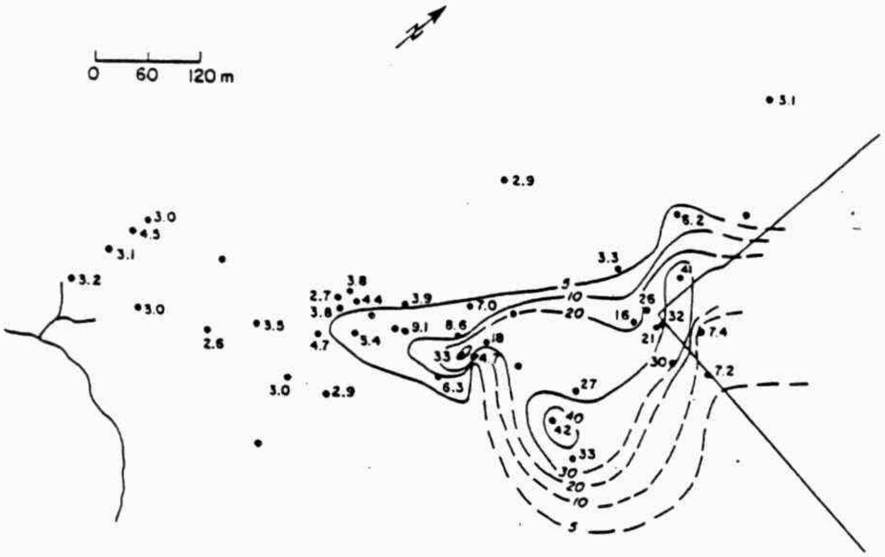


Figure 2.8 cont'd.

ETHYLBENZENE, JULY 85



O - XYLENE, JULY 85



p/m - XYLENE, JULY 85

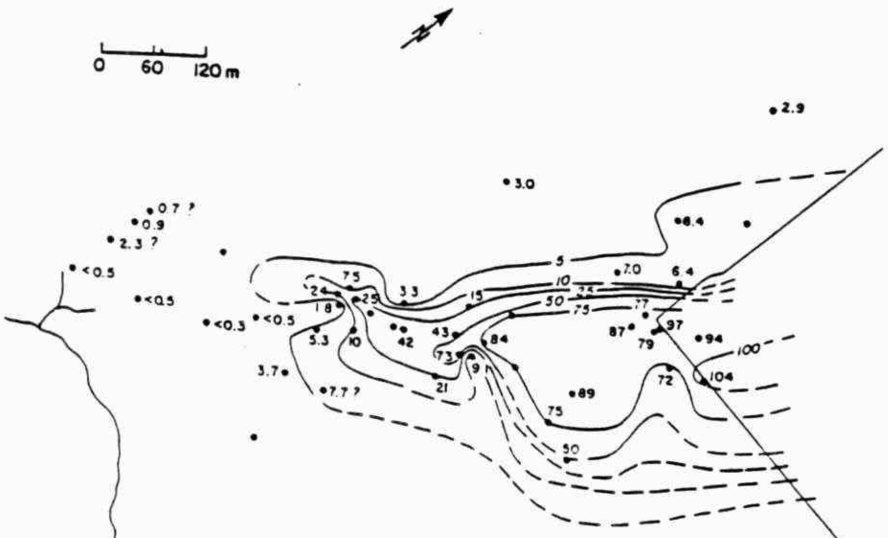
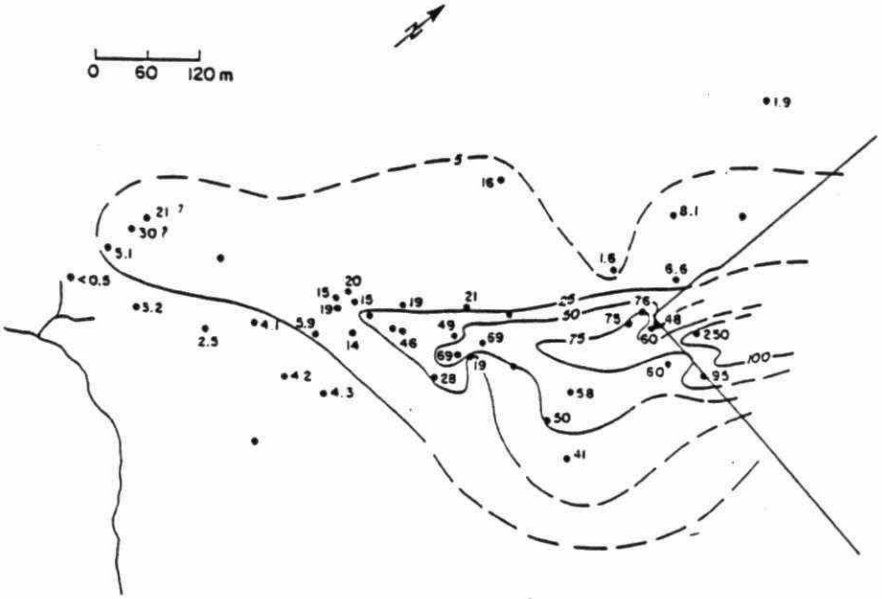


Figure 2.8 cont'd.

1,2,4 - TMB, JULY 85



NAPHTHALENE, JULY 1985

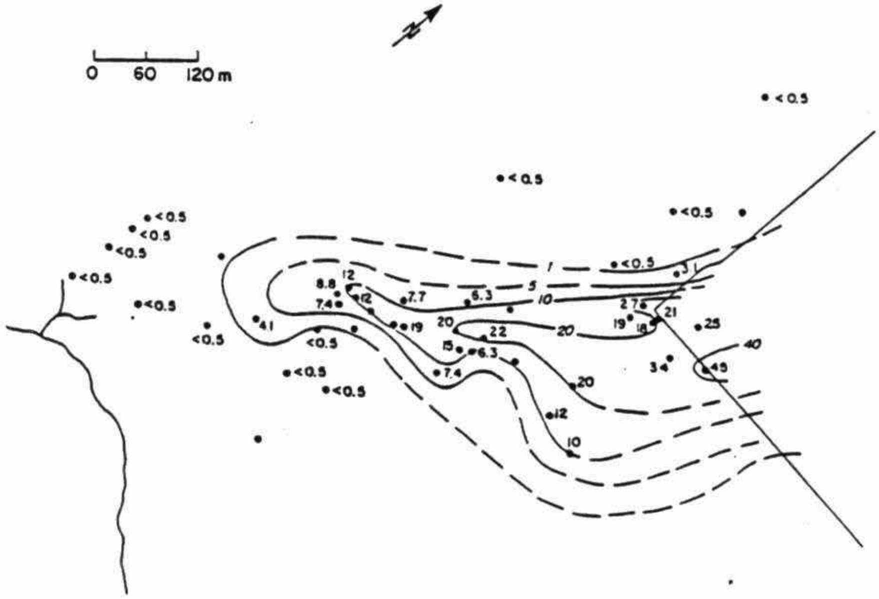


*Figure 2.9*: The vertical distribution of chloride and various aromatic hydrocarbons along cross-section AA' (see Figure 2.6) at the North Bay landfill site.

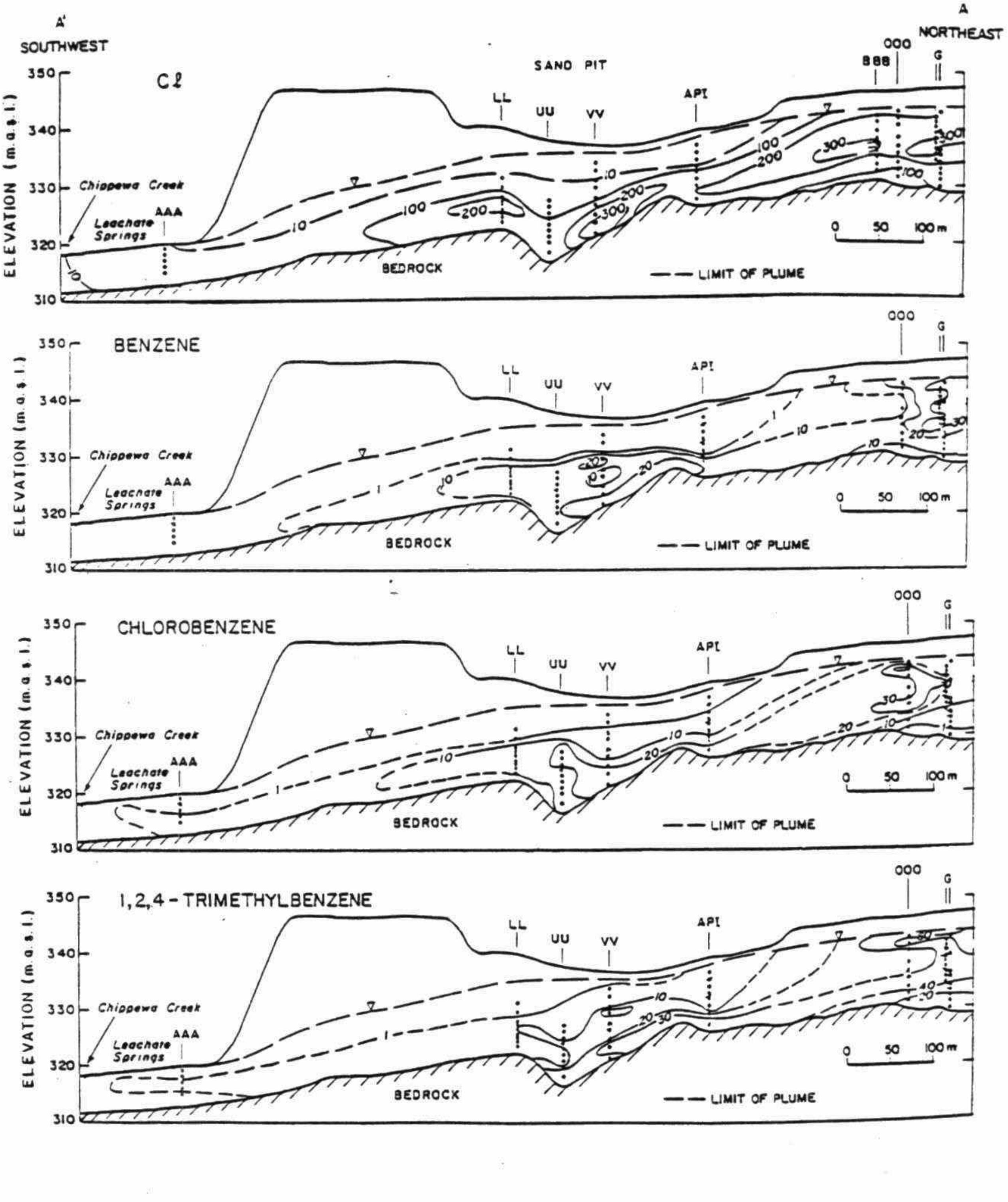
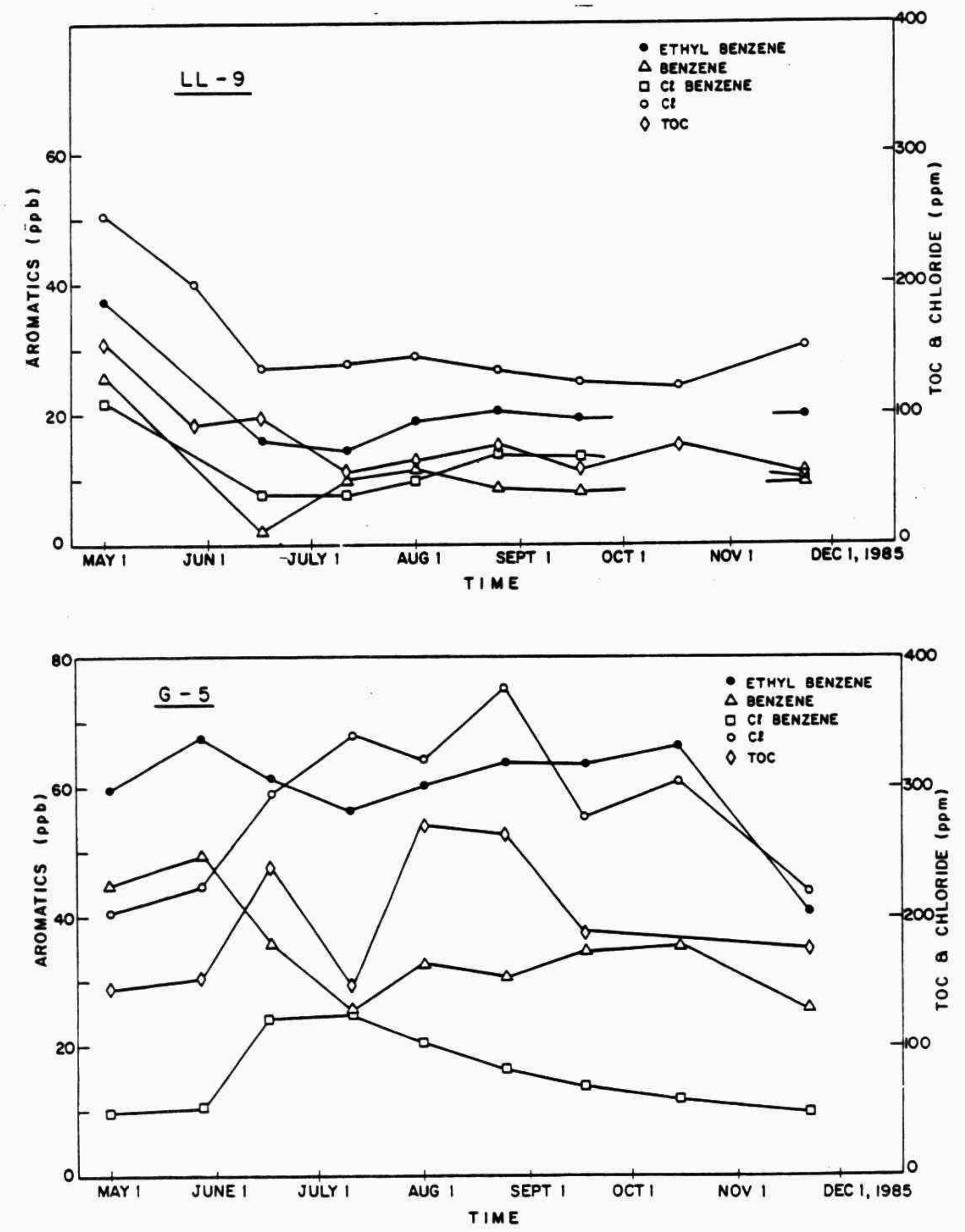


*Figure 2.10*: Temporal variability of some contaminants in groundwaters from two piezometer points at the North Bay landfill site.



The most extensive sampling of this plume occurred in 1985. The plan views of maximum chloride and organic concentrations at each multilevel piezometer are shown in Figure 2.8 for July 1985 and for October 1985 (chlorobenzene only). Comparison of July and October chlorobenzene distributions reveals little substantial difference. A similar comparison was found for Cl, TOC and most aromatic hydrocarbons. This lack of major temporal variation suggests that the plume is approaching a steady-state condition. That is, contaminant distributions controlled by both the input from the landfill and the attenuation processes (dispersion, biodegradation) appear rather steady. If this observation is correct, then the extent of the organic plumes reflects the efficiency of natural attenuation mechanisms to remove or reduce these contaminants.

Attenuation of chloride concentrations is due to dispersive dilution-mixing of leachate with low-Cl, background groundwater. The aromatic hydrocarbons are not significantly influenced by sorptive retardation, so it is assumed that they undergo the same dispersive dilution as chloride. This dispersive dilution is estimated by averaging the maximum solute concentrations: 1) near the landfill (G, G', BBB and NNN), 2) about 350 m downgradient (LL, U, UU, JJJ) and 3) about 620 m downgradient in the discharge area (AAA, EEE, BB and FFF), and dividing the average maximum chloride concentration at 2) or 3) by that at 1). Results are shown in Table 2.5.

Also shown in Table 2.5 are the dilutions for selected aromatic hydrocarbons calculated in a similar manner. Where dilutions exceed the chloride dilution, attenuation processes in addition to dispersion must be operational. In this aquifer, microbial degradation is the most likely additional attenuation process. This analysis suggests that: 1) toluene and p/m-xylene are most rapidly biodegraded, 2) benzene, ethylbenzene and naphthalene are greatly attenuated by biodegradation, 3) o-xylene and 1,2,4-trimethylbenzene degradation does not continue past 350 m in the plume, 4) chlorobenzene initially appears to biodegrade, but it is not significantly more diluted than chloride after 620 m. This interpretation would suggest that the order of increasing persistence among these aromatic hydrocarbons in this landfill leachate plume is: toluene < p/m-xylene < napthalene ≈ ethylbenzene < benzene < o-xylene < 1,2,4-trichmethylbenzene < chlorobenzene. Some of the irregular dilutions shown in Table 2.5 could be due to the production of some aromatics during anaerobic degradation of other organics. For example, Grbic-Galic and Young (1985) noted the transient appearance of benzene and toluene during methanogenesis of ferulate and benzoate-model compounds for anaerobic degradation studies. Also, the piezometers were arbitrarily selected for computing average concentrations along the plume and this may contribute to the apparent irregular dilutions.

How well does an indicator parameter like Cl, reflect the distribution of organic contaminants? To evaluate the linear correlation between this indicator and trace organic parameters, a series of simple statistical tests were performed. All the pairs of chloride plus benzene, chlorobenzene, and 1,2,4-trimethylbenzene for groundwaters sampled in 1985 from the multilevel piezometers G, LL and AAA were used. Linear regression equations were developed for the chloride-organic pairs and the linear correlation coefficients calculated. The results are shown in Table 2.6. Near the landfill at piezometer G, there is essentially no linear correlation of chloride with the trace organics. This suggests that the input leachate is rather inhomogeneous and that the landfill is not a constant source of these contaminants. Further along the flow system at piezometer LL, the contaminants benzene and chlorobenzene show a much better correlation with the indicator parameter. At LL, the 1,2,4-trimethylbenzene concentrations were often below the analytical detection limit (about 0.2 ug $L^{-1}$) and so no correlation was attempted. This improved correlation at LL is intriguing. Could it be that the processes controlling contaminant transport, particularly dispersion, sorption and biodegradation, are acting to smooth the erratic Cl-organic relationships observed near the landfill? This aspect is under investigation. In the discharge zone the organic concentrations have dropped considerably so that most samples contained only undetectable levels of organics, except for benzene. The Cl-benzene correlation was established by assigning the undetectable benzene concentrations as the detection limit (0.2 ug $L^{-1}$). The resulting correlation is very poor, in part due to this assignment. However, biodegradation of the aromatic hydrocarbons probably contributes to the lack of Cl-benzene correlation; biotransformation removes benzene even from high-Cl samples, leaving variable Cl concentrations in samples, with low and less-variable benzene concentrations.

Because of time and financial constraints, leachate plumes are normally monitored infrequently and analysis of indicator parameters is emphasized. Our experience at the North Bay site indicates this is adequate to establish a gross picture of the plume behaviour, but may be inadequate to discuss more subtle, but still significant, changes in contaminant concentrations. Before the concentration of an indicator parameter such as chloride can be used to infer the concentration of another contaminant, a strong correlation of these parameters must be shown throughout the plume. This is certainly not the case in the North Bay plume.

It may be suggested that only a few parameters be selected for detailed monitoring at sites of groundwater contamination. These *critical parameters* should include some organics if organic contaminants are present. The choice is likely to be made from the results of leachate analysis and would include mobile, potentially-toxic compounds. Based on the analysis of piezometer G-5 (Table 2.5) adjacent to the North Bay landfill, p/m-xylene could have been included as a critical parameter because of its high concentration relative to other aromatics. However, 620 m down the flow system, p/m-xylene concentrations are very low (2 ug $L^{-1}$); much lower than say 1,2,4-trimethylbenzene or chlorobenzene (see Table 2.5). Thus, this choice of p/m-xylene as a critical parameter would be misleading in that the significant level of contamination 620 m from the site would not have been recognized. This illustrates the complexity that variable biodegradation behaviour among organics can create in designing effective plume monitoring strategies.

In addition, reactive contaminants are generally unlikely to remain well-correlated to non-reactive indicator parameters during transport. This is particularly true for organic contaminants which are undergoing biodegradation. To illustrate this, consider the decrease in chloride benzene and toluene concentrations in groundwaters sampled down the flow system (see Table 2.6). Whereas the chloride concentration decreased almost five-fold, the benzene concentration decreased ten-fold and the toluene concentration decreased twenty-five-fold! Barker et al. (1986) cautioned that such dramatic organic concentrations declines could not be directly interpreted in terms of the extent of biodegradation due to the considerable temporal variability of both chloride and organic inputs from the landfill. However, even the cautious interpretation of the differences between chloride and organic decline must invoke biotransformation of organics. In any case, the inability to accurately predict organic contaminant concentrations from indicator parameter data is obvious.

### 2.3.3 Conclusions

The leachate plume emanating from the North Bay landfill has been discharging near a creek about 800 m distant since before 1980. All parameters are undergoing significant dispersive dilution during this transport, which may take 2 to 4 years. Aromatic hydrocarbon contaminants undergo even greater attenuation than unreactive species. Their biodegradation is considered the most likely mechanism for this additional concentration reduction. Volatile halocarbons are reduced to non-detectable levels within about 200 m of the landfill, probably due to their biodegradation under the strongly anaerobic leachate plume conditions.

Considerable temporal variability in both indicator parameter (Cl, TOC) and trace organic concentrations was observed at individual wells, although the general shape and contaminant distributions appear to be similar from 1980 to 1985. Indicator parameters were adequate to describe the general extent and level of contamination, but were not suitable indicators of subtle aspects of organic contaminant distributions in the leachate plume.

Anaerobic degradation of both volatile halocarbons and many aromatic hydrocarbons occurs in strongly reducing (methanogenic) leachate plumes. This biodegradation combines with dispersive dilution to limit the trace organic concentrations at the discharge area to levels of minimal environmental concern.

*Table 2.3*: Inorganic Parameters in Groundwater from the North Bay Landfill Leachate Plume. Concentrations are in mg $L^{-1}$ Unless Noted Otherwise. Samples Collected 21/11/83

| **Parameter** | **Piezometer** | | | |
|---|---|---|---|---|
| | G-5 | LL-5 | LL-9 | AAA-5 |
| pH | 6.9 | 6.8 | 6.7 | 6.4 |
| Conductivity (umho/cm) | 4510 | 1740 | 2650 | 560 |
| Ca | 232 | 106 | 123 | 50.0 |
| Mg | 99 | 37.5 | 56 | 14.4 |
| Na | 285 | 109 | 197 | 38 |
| K | 230 | 56.5 | 81.5 | 11.0 |
| Alkalinity (as $CaCO_3$) | 2070 | 711 | 970 | 220 |
| F | 0.06 | 0.06 | 0.04 | 0.04 |
| Cl | 332 | 138 | 226 | 50.0 |
| $SO_4$ | 15.0 | 8.0 | 13 | 10.0 |
| $NO_3$ (as N) | <0.1 | <0.1 | <0.1 | <0.1 |
| Kjeldahl N (as N) | 192 | 53.5 | 76.0 | 12.0 |
| Ammonium (as N) | 185 | 47.5 | 68.0 | 7.0 |
| Nitrite (as N) | 0.06 | 0.06 | 0.08 | 0.06 |
| DOC | 129 | 46.5 | 82.0 | 12.9 |
| Fe | 82 | 90 | 140 | 22 |
| Mn | 5.6 | 5.6 | 8.2 | 3.4 |
| As (ug L) | < 1 | 2 | 2 | 1 |
| Ba " | 220 | 1500 | 2600 | 270 |
| Cd " | <10 | <5 | 80 | <5 |
| Cr " | 33 | 23 | 38 | 11 |
| Cu " | <9 | <5 | <5 | <5 |
| Ni " | 79 | 63 | 100 | 21 |
| Pb " | 67 | 88 | 160 | <30 |
| Se " | <1 | <1 | <1 | <1 |
| Zn " | 6 | 9 | 11 | 8 |

*Table 2.4*: Selected Organic Parameters in Groundwater from the North Bay Landfill Leachate Plume. Concentrations in ug $L^{-1}$ Unless Noted Otherwise.

| **Parameter** | **Piezometer**<br>**G-5** | **LL-9** | **AAA-5** |
|---|---|---|---|
| MOE Lab (20/11/83) | | | |
| Lindane ($ng/L^{-1}$) | 1 | <1 | <1 |
| Dieldrin " | <1 | 4 | 2 |
| DDD " | <5 | 25 | <5 |
| | | | |
| Biphenyl | 3 | 1 | n.d. |
| Polyethylene Glycol Deriv. | 180 | 10 | n.d. |
| Dimethylbenzoic Acid | n.d. | 13 | n.d. |
| Tributyl Phosphate | 22 | 15 | 2 |
| Phthalates | 110 | 50 | 10 |
| Phenols | 10 | 15 | n.d. |
| Hydroxybenzothiazole | 10 | <15 | 3 |
| | | | |
| Chloroform | 0.9 | - | n.d. |
| 1,2-Dichlorobenzene | 13 | 14 | 3 |
| Acetone | 6 | 2.4 | 0.6 |
| Diethyl Ether | 15 | 20 | 4 |
| Tetrahydrofuran | 9 | 5 | 0.6 |
| Methyl Ethyl Ketone | 2 | 0.8 | n.d. |
| Thiophene | 0.6 | n.d. | n.d. |
| 1,4-Dioxane | 0.6 | n.d. | n.d. |
| Diethyl Sulphide | 3 | n.d. | n.d. |
| Hexanol | 11 | 6 | n.d. |
| Fenchone | 48 | 27 | n.d. |
| Camphor | 19 | n.d. | n.d. |
| UW Lab (26/10/84) | | | |
| Benzene | 51 | 13 | 1.6 |
| Toluene | 1.3 | n.d. | n.d. |
| Chlorobenzene | 9.1 | 6.9 | n.d. |
| Ethylbenzene | 58 | 13.6 | n.d. |
| p-Xylene | 90 | - | n.d. |
| o,-m-Xylene | 7.6 | - | n.d. |
| Cumene | 6.6 | 2.8 | n.d. |
| 1,2,4-Trimethylbenzene | 51 | 2.7 | n.d. |
| Naphthalene | 15 | n.d. | n.d. |

n.d.: not detected
 - : not determined

*Table 2.5*: Dilution of chloride and selected aromatic hydrocarbons within the North Bay leachate plume. See text for details of calculation.

| Solute | Average Maximum Concentrations (ug $L^{-1}$) And Concentrations Relative to 1) | | | Attenuation Mechanisms |
|---|---|---|---|---|
| | 1) Adjacent to Landfill | 2) 350 m Downgradient | 3) 620 m Downgradient | |
| **Chloride** | 330000<br>1 | 230000<br>0.70 | 66000<br>0.20 | dispersion |
| **Benzene** | 28<br>1 | 13<br>0.46 | 2.9<br>0.10 | dispersion,<br>biodegradation |
| **Toluene** | 19<br>1 | 0.98<br>0.05 | 0.75<br>0.04 | dispersion,<br>biodegradation |
| **Chlorobenzene** | 35 | 19<br>0.54 | 5.5<br>0.16 | dispersion,<br>perhaps biodegradation |
| **Ethylbenzene** | 60<br>1 | 31<br>0.52 | 2.1<br>0.04 | dispersion,<br>biodegradation |
| **p/m-Xylene** | 85<br>1 | 15<br>0.18 | 1.1<br>0.01 | dispersion,<br>biodegradation |
| **o-Xylene** | 24<br>1 | 3.7<br>0.15 | 3.4<br>0.14 | dispersion,<br>biodegradation |
| **1,2,4-Trimethylbenzene** | 65<br>1 | 17<br>0.26 | 15<br>0.23 | dispersion,<br>biodegradation |
| **Naphthalene** | 21<br>1 | 10<br>0.48 | <0.05<br><0.02 | dispersion,<br>biodegradation |

*Table 2.6*: Slope (m) and intercept (c) for the relationship between chloride and various organic concentrations.

| Location | Organic | No. of Data | Slope (m) | Intercept (c) | Linear Correlation (r) |
|---|---|---|---|---|---|
| G | Benzene | 66 | 1.30 | 31.0 | -0.0968 |
| | Chlorobenzene | 66 | 2.51 | 13.8 | 0.0231 |
| | 1,2,4-Trimethylbenzene | 66 | -0.145 | 90.6 | -0.511 |
| LL | Benzene | 72 | -0.0743 | -0.13 | 0.773 |
| | Chlorobenzene | 72 | 0.0551 | 1.78 | 0.622 |
| AAA | Benzene | 21 | -1.18 | 1.61 | -0.113 |

## 2.4 New Borden Landfill

### 2.4.1 Site Hydrogeology

In 1976, a new landfill began operation at Canadian Forces Base Borden, on a moderately sloping site, underlain by silty sand till. The New Borden landfill has three equally spaced cells, 60 m by 150 m, formed in excavations between 2 m and 5 m below grade and built up to 8 m to 10 m above grade. The first cell was completed in 1979 and the second cell in 1984.

The stratigraphy of the site is described by Carey (1985) using previously gathered information, and information from continuously sampled boreholes at several locations. The most important zone hydrogeologically is the silty sand till, in which the base of each landfill cell is located. This sand till is fractured in the top 1 m to 2 m, and is overlain by a fractured silty clay till. Vertical groundwater flow is controlled by a basal clayey silt till.

Previously installed standpipes and piezometers numbering 49, supplemented by the installation of a further 46 piezometers, supplied both samples for the dissolved organic carbon and chloride plume delineation, and groundwater level information for the description of the groundwater flow system. A well developed contaminant plume, mapped using DOC and Cl concentrations, has been produced by the first two landfill cells. The plume has extended approximately 200 m in the 8 years since landfilling operations were begun, with the direction of development following the original groundwater flow pattern, and the chemistry controlled to a greater extent by the older cell. DOC and Cl information is available as early as 1976, providing a valuable time record of the development of the plume.

Field rising head permeability tests were performed in all piezometers as an aid to description of the stratigraphy and groundwater flow system. In addition, laboratory analyses, consisting of hydrometer tests and falling head permeameter tests were performed. Hydraulic conductivities that resulted from field tests in the silty sand till ranged from 2.3 x $10^{-4}$ cm $s^{-1}$ to 1.8 x $10^{-6}$ cm $s^{-1}$. Analysis based on the grain-size distribution of the silty sand till resulted in average hydraulic conductivities of 8.1 x $10^{-4}$ cm $s^{-1}$ and 1.5 x $10^{-3}$ cm $s^{-1}$, while laboratory tests produced values of 2.3 x $10^{-4}$ cm $s^{-1}$ and 1.1 x $10^{-4}$ cm $s^{-1}$. Previous work reported K values of 1.1 x $10^{-5}$ cm $s^{-1}$ to 5.9 x $10^{-5}$ cm $s^{-1}$. Combining all the various values results in an average hydraulic conductivity of 5.0 x $10^{-5}$ cm $s^{-1}$ for the silty sand till.

### 2.4.2 Sampling

Following some preliminary sampling in 1984, groundwaters at the New Borden landfill site were sampled on three occasions in 1985 - 05 June, 02 July and 20 August. Where the piezometeric surface was within about 7 metres of the surface, a peristaltic pump was used to sample the PVC well piezometers. After removal of the standing water and sufficient recharge of the well (less than 1 hour), groundwater was drawn via teflon tubing and a short length of silicon tubing in the pumps. Other wells were sampled with an all-metal bailer. Samples for volatile organics were collected in organic-free 60 $cm^3$ hypovials without headspace, about 0.2 $cm^3$ of 10% sodium azide bacteriacide was added and a teflon-faced silicon septum was cripped securely onto the hypovial. One-litre samples were collected from two wells for extractable organic analyses. These glass bottles were organic-free and were sealed without headspace using a teflon-faced septum.

### 2.4.3 Analyses

One-litre samples were solvent extracted with dichloromethane under acidic and basic conditions and the extract reduced in volume using methods similar to those described by Reinhard et al. (1984) and Patrick et al. (1985). An aliquot was injected onto a HP5890 gas chromatograph coupled to a HP5970 mass selective detector.

The mass spectra of all significant peaks were compared to the mass spectra of organics in both the full NBS Mass Spectral Library and the EPA organic priority pollutant subset library. Match qualities in excess of 8000 (80% of perfect match) were generally considered adequate for tentative compound identification, but some judgement was used in assigning identification.

Samples collected for volatile halocarbon and volatile aromatic hydrocarbon analyses were solvent extracted in the hypovials with pentane or hexane and an aliquot of the solvent analyzed by gas chromatography. Peak identifications and peak purity was occasionally monitored by GC/MS analysis with an identical column. Methods are described in Reinhard et al. (1984) and Patrick et al. (1985) and are included in Appendix E.

### 2.4.4 Results

The major organics tentatively identified in contaminated groundwater for piezometers M-7 and B84-1 are listed in Table 2.7. Various fatty acids were the dominant organics identified. Other than in the volatile class, no EPA priority organic pollutants were tentatively identified (phenol, at less than 10 ppb excepted). Consequently, studies at the New Borden landfill site concentrated upon the volatile halocarbons and aromatics.

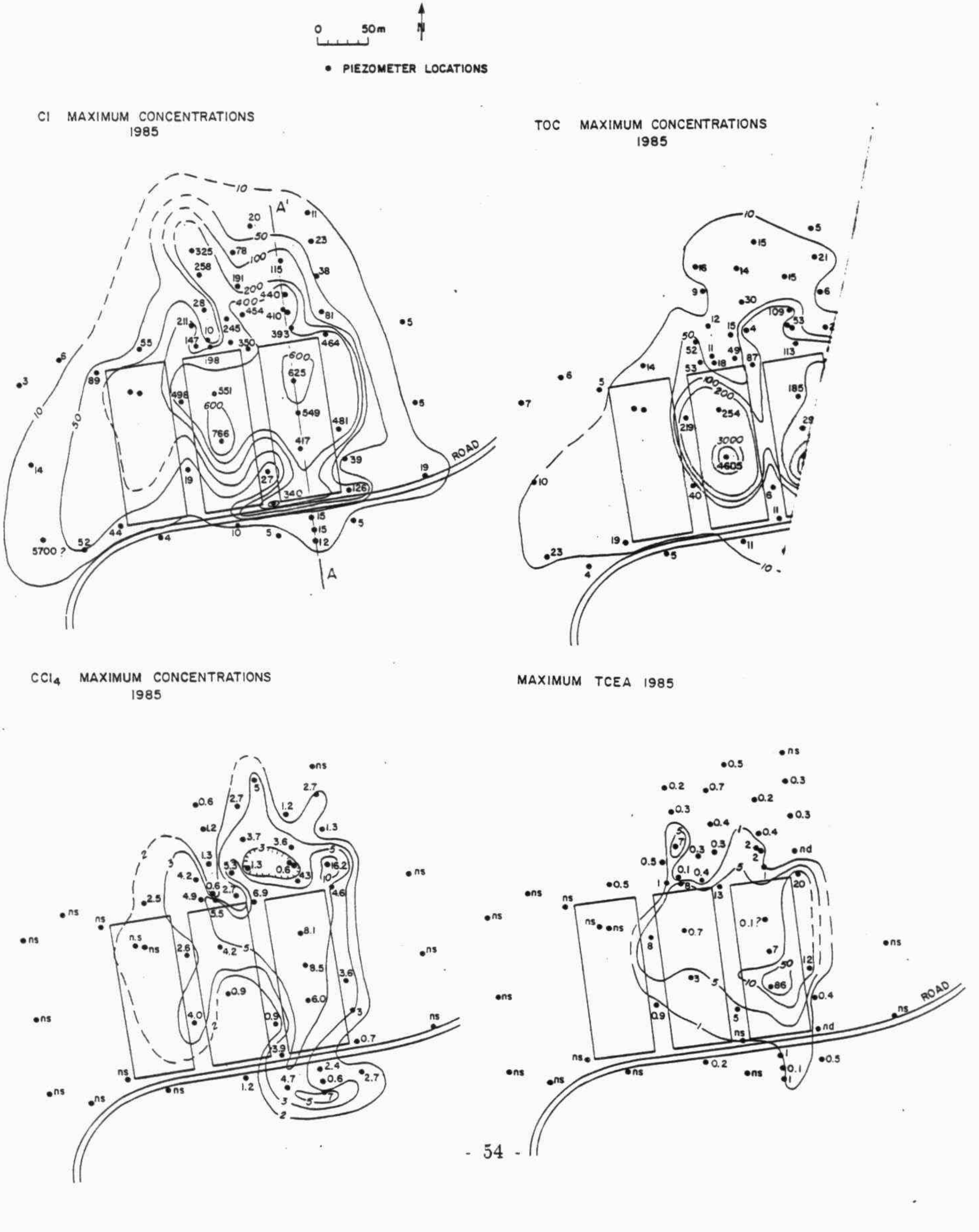
The relationships between the indicator parameters-Cl and TOC and the volatile halocarbon and aromatic concentrations was evaluated. The correlation between the indicator parameters themselves is poor (correlation coefficient of 0.50). Similarly, poor correlations between chloride and the organic parameters were found (correlation coefficients always less than 0.50). A better correlation between TOC and the organic contaminant concentrations was often found. Correlation coefficients were often higher than 0.70 among the aromatics. This suggests that a more direct relationship of source, migration rate and reactions exists within the organic fraction than between the inorganic chloride and organics.

The spatial distribution of indicator parameters and selected organic contaminants is illustrated in Figures 2.11 to 2.13. Figures 2.11a to 2.11j show the plan view of the maximum concentrations found in 1985 of Cl, TOC, carbon tetrachloride ($C\ Cl_4$) trichloroethylene (TCEY), trichloroethane (TCEA), toluene (TOL) and ethylbenzene (EBENZ), p/m xylene, 1,2,4-trimethylbenzene, and naphthalene, respectively. These diagrams must be viewed with caution since the three-dimensional aspect of the plumes is not necessarily accurately represented.

The Cl and TOC plots outline the probable extent of leachate impact, although it is not clear whether the 10 or 50 mg $L^{-1}$ contour divides background from impacted groundwater. For TOC, the 10 mg $L^{-1}$ contour may slightly overestimate the extent of the leachate plume in 1985. Sampling was concentrated upon the older cells and so the western portion of the network has received little attention. It is evident that the groundwater contamination extends at least 150 m northward in the direction of regional groundwater flow. The low-level contamination to the west and south of the cells is not likely, hydrogeologically, to have been derived from the waste disposal cells. It could be an artifact of high background values in groundwaters or could be the result of other contaminant sources in this area.

CCL4 and TCEA were detected ($> 0.1$ ug $L^{-1}$) in almost all wells at least once (Figure 2.16c and d). The low concentration values ($< 1$ ug L) are either the result of minor contamination from the PVC wells, from sampling equipment or from laboratory contamination or they indicate that TCEA and CFORM are at least as mobile as Cl. The distribution of TCEY is more restricted (Figure 2.11d). Concentrations decrease from 750 ug $L^{-1}$ in leachate within the wastes of cell 1 to less than 1 ug $L^{-1}$ within 50 m of the cells. This suggests that the combined processes of dispersion, retardation and biodegradation are limiting TCEY migration. TCEY is slightly less mobile (more highly sorbed and therefore retarded) than TCEA or CCL4 in aquifers.

*Figure 2.11*: The areal extent of the maximum concentration of selected contaminants from the New Borden landfill site



• PIEZOMETER LOCATIONS

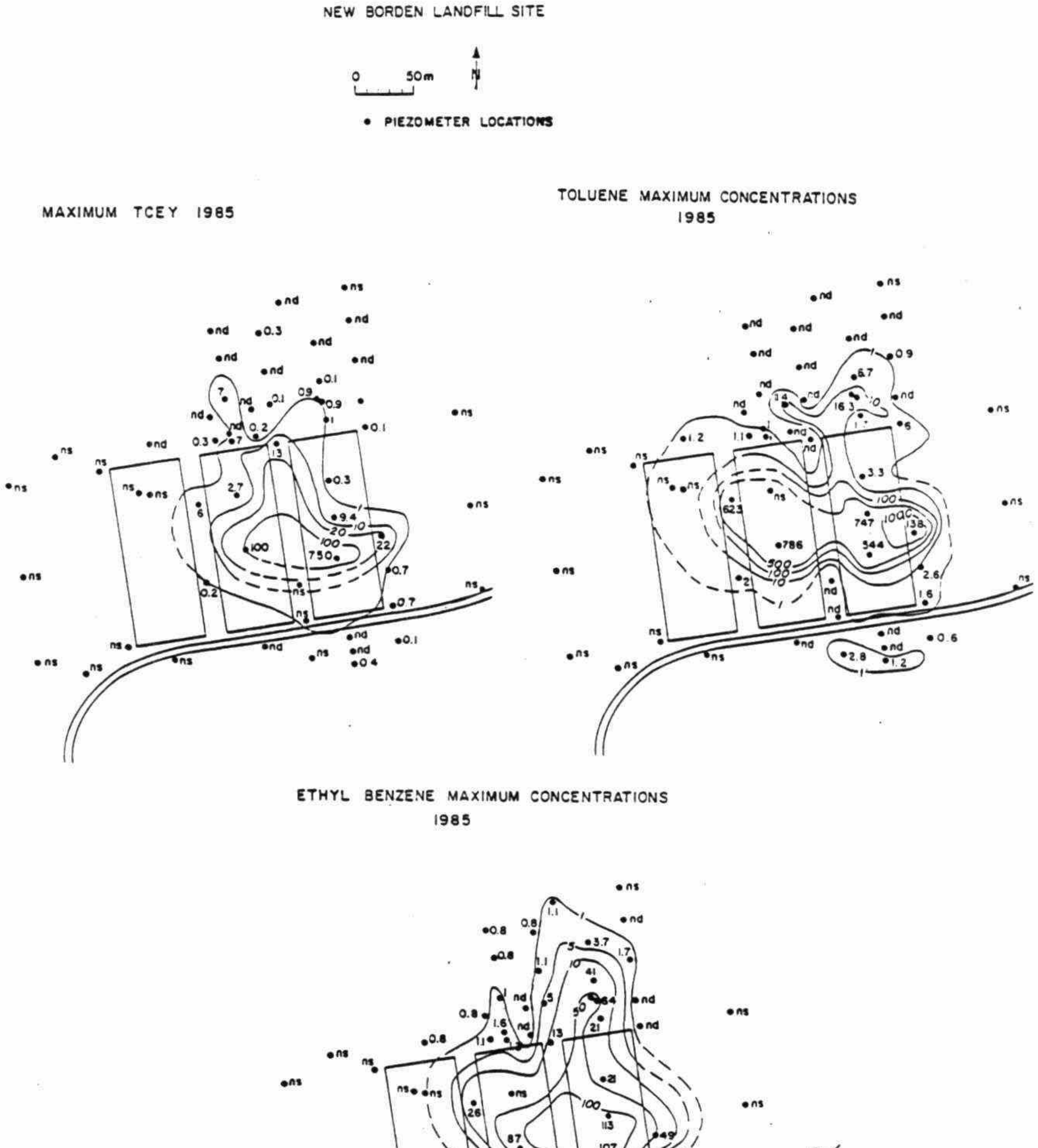
Cl MAXIMUM CONCENTRATIONS 1985

TOC MAXIMUM CONCENTRATIONS 1985

$CCl_4$ MAXIMUM CONCENTRATIONS 1985

MAXIMUM TCEA 1985

Figure 2.11 cont'd.



NEW BORDEN LANDFILL SITE

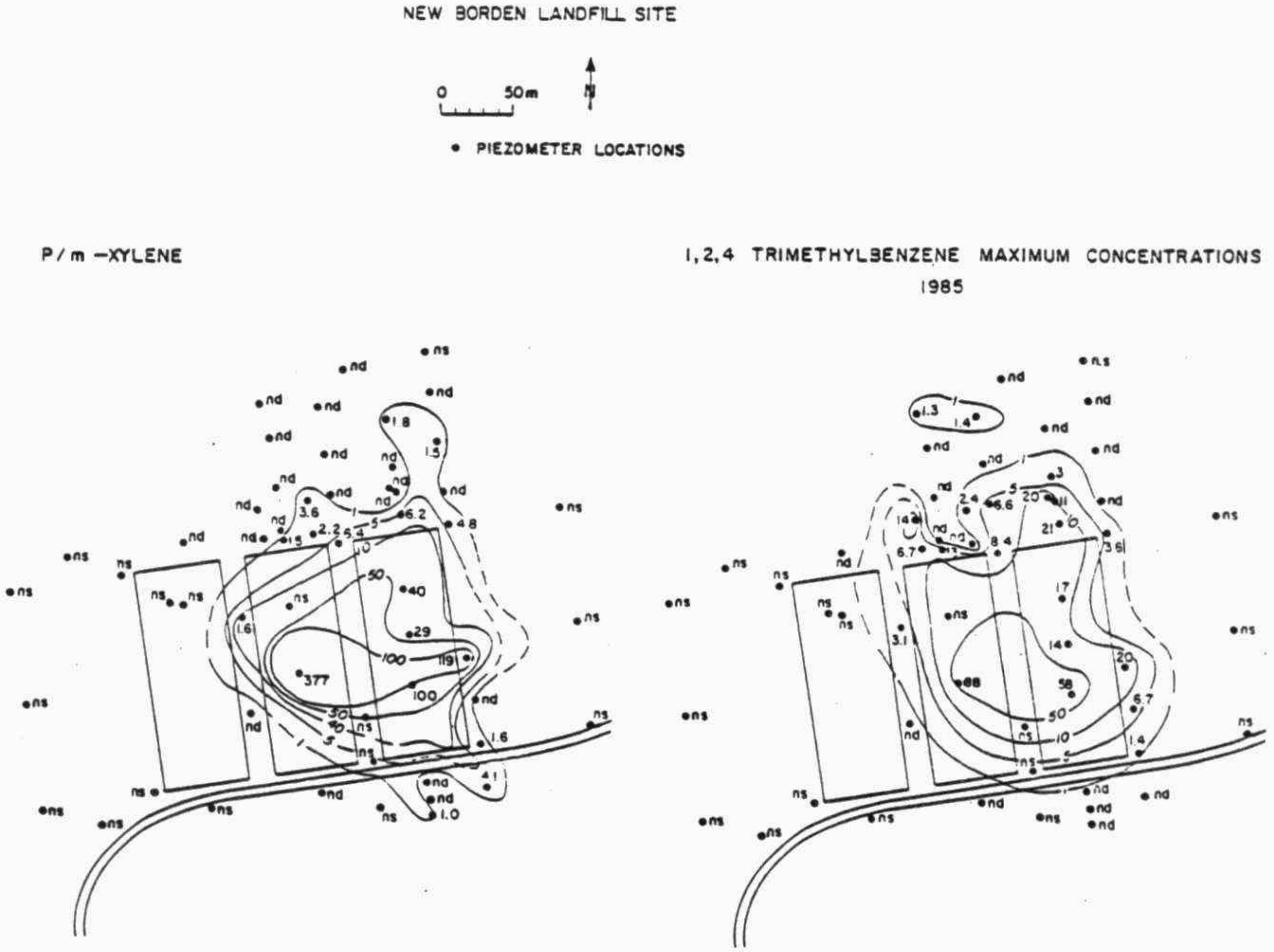
MAXIMUM TCEY 1985

TOLUENE MAXIMUM CONCENTRATIONS 1985

ETHYL BENZENE MAXIMUM CONCENTRATIONS 1985

Figure 2.11 cont'd.

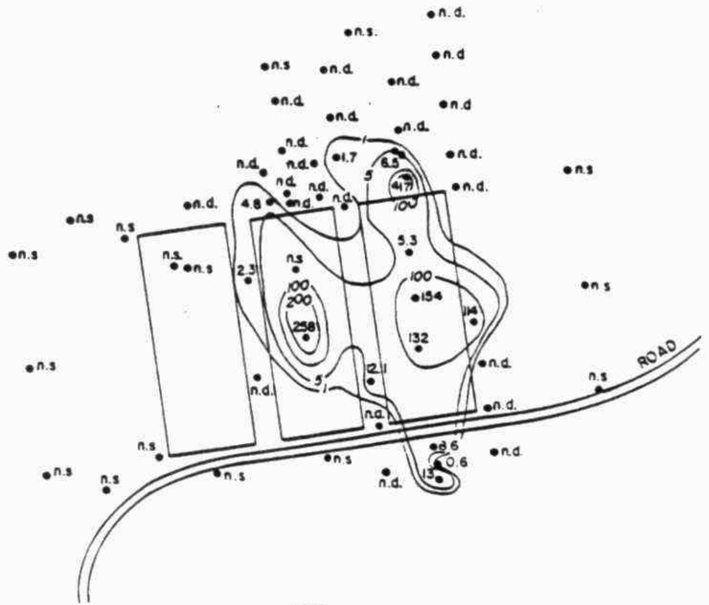
NEW BORDEN LANDFILL SITE



P/m –XYLENE

1,2,4 TRIMETHYLBENZENE MAXIMUM CONCENTRATIONS
1985

NAPTHALENE MAXIMUM CONCENTRATIONS
1985



This is consistent with the more-limited plume of TCEY compared to TCEA or CCL4. The concentration reduction of TCEY appears to be much greater than for TCEA or CCL4, suggesting more rapid biodegradation of TCEY in contaminated groundwaters.

Ethylbenzene (EBENZ) is widely distributed at low concentrations at this site (Figure 2.11). This could reflect the occurrence of < 1 ug $L^{-1}$ ethylbenzene in background groundwaters since ethylbenzene is a naturally-occurring organic compound. It could also reflect the pervasive transport of ethylbenzene throughout the plume with concentration reduction due mainly to dispersive processes which are also responsible for reductions in Cl concentrations (Figure 2.11a). Toluene (TOL, Figure 2.11f) shows a more-restricted distribution than ethylbenzene. This difference is not due to enhanced sorptive retardation of toluene since toluene is less retarded in aquifers than ethylbenzene. On the other hand, toluene is more easily biodegraded than ethylbenzene, at least under aerobic conditions. Thus, the restricted migration of toluene likely reflects its biodegradation as the leachate plume becomes more aerobic during transport. Similarly, the spatial distributions of 1,2,4-trimethylbenzene, the xylenes and naphthalene resemble the toluene distribution most closely, suggesting their migration is also limited by biodegradation.

Figures 2.12 and 2.13 shows the distribution of chloride (June, 1984 and August, 1985) and selected volatile organics in groundwaters sampled in cross-section AA' through the oldest landfill (see Figure 2.11a) cell. The underlying clayey silt till was found to be less permeable than the silty sand till (Appendix C-1) and so the cross-sections were contoured on the assumption that contaminants would migrate in the sand till.

The shape of the Cl plume (Figure 2.12) has not changed much from 1984 to 1985 except that the 100 mg $L^{-1}$ contour has extended from M17 to M18 - a distance of about 35 m.

*Figure 2.12*: The distribution of chloride, carbon tetrachloride and toluene in the vertical cross-section AA' (see Figure 2.10) at the New Borden landfill site

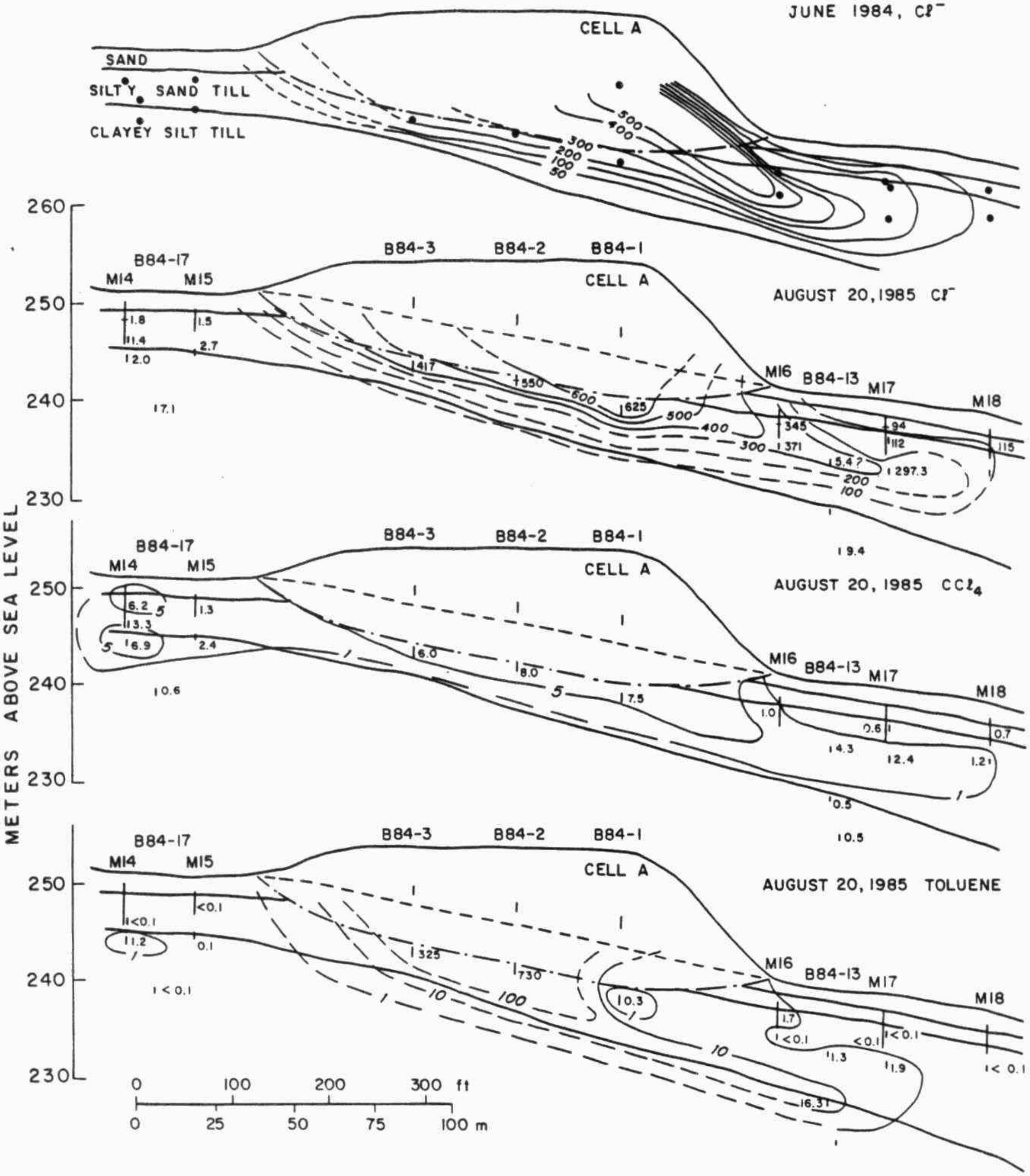


*Figure 2.13*: The distribution of selected organics in the vertical cross-section AA' (see Figure 2.10) at the New Borden landfill site

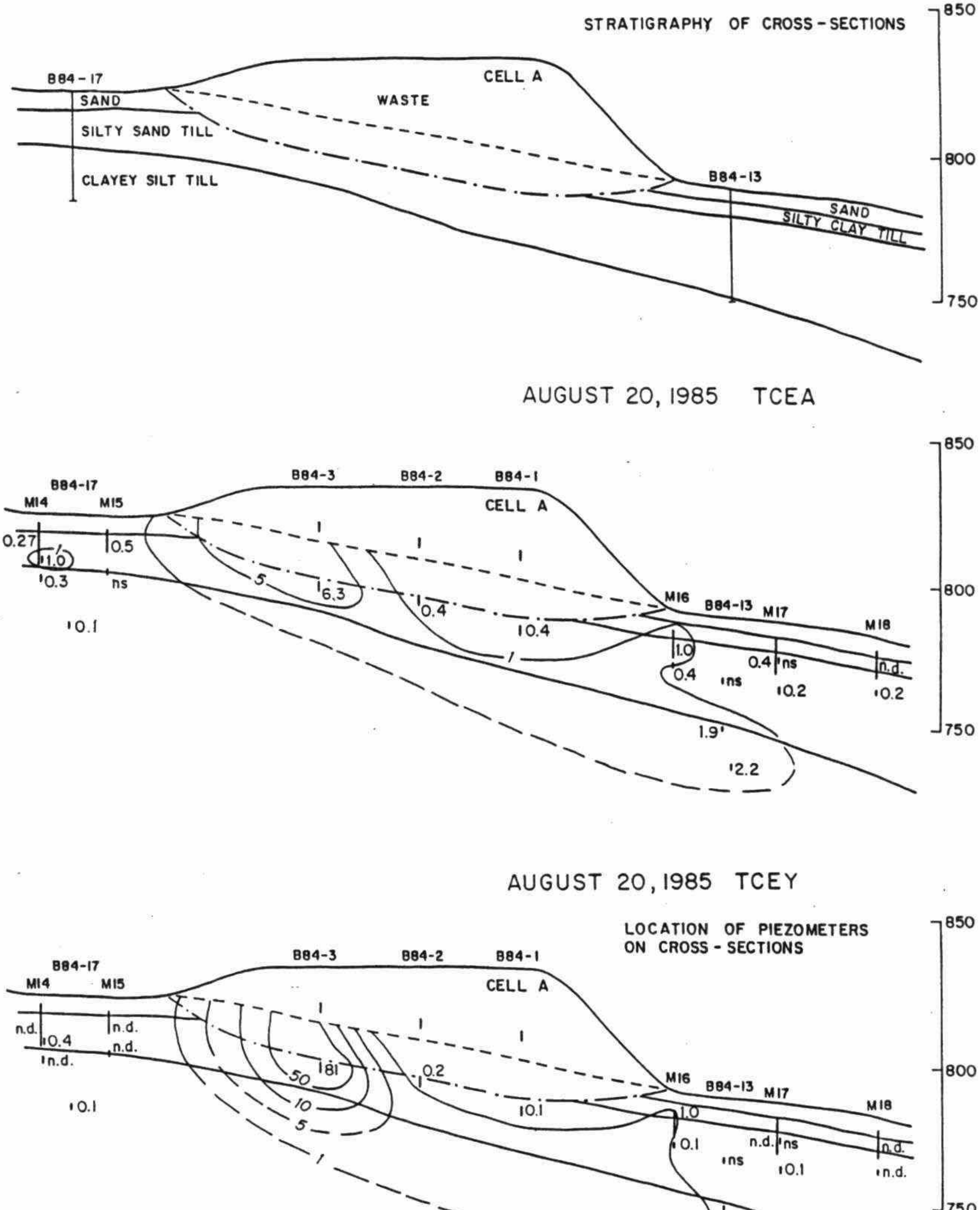
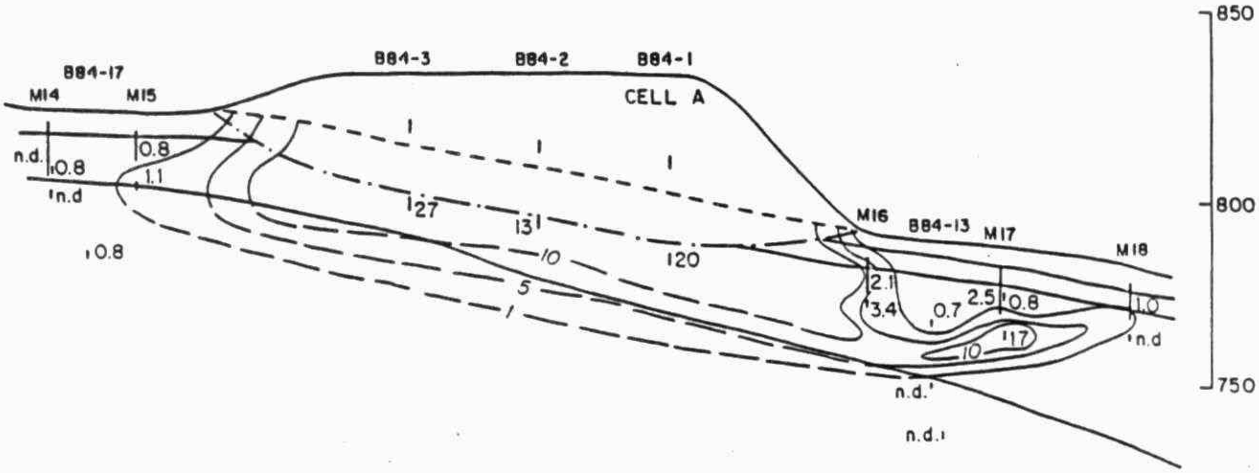


Figure 2.13 cont'd.


AUGUST 20, 1985 ETHYLBENZENE

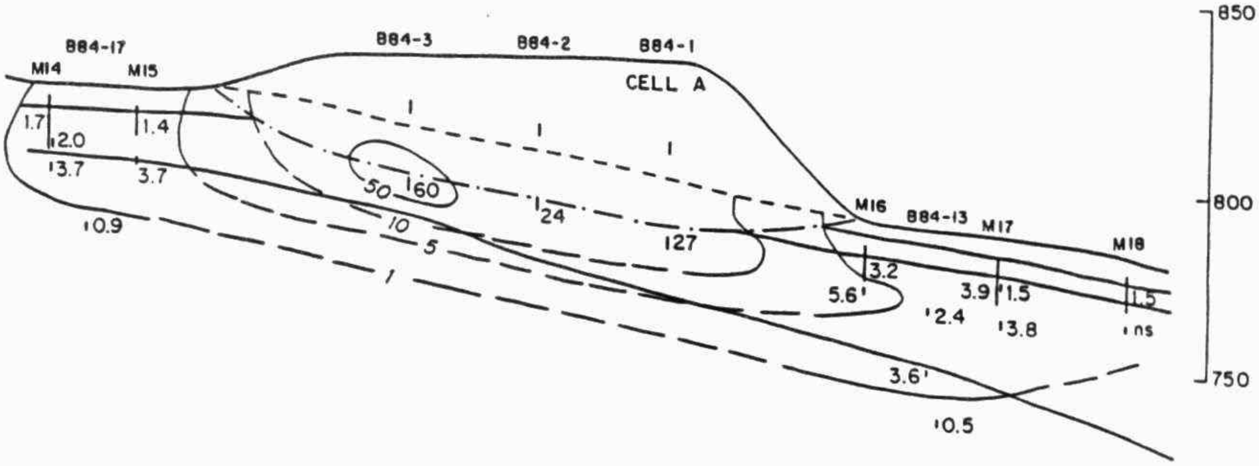
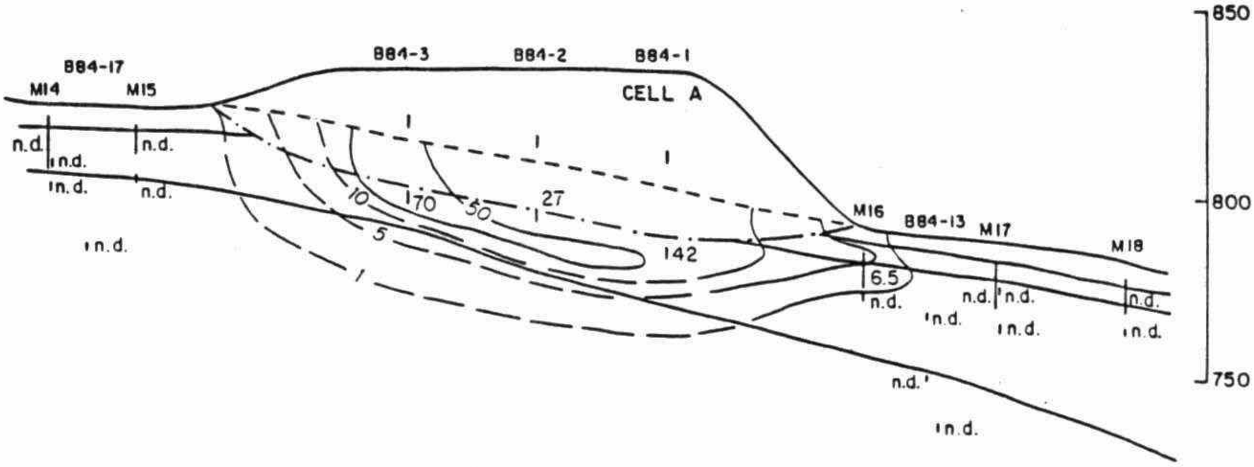
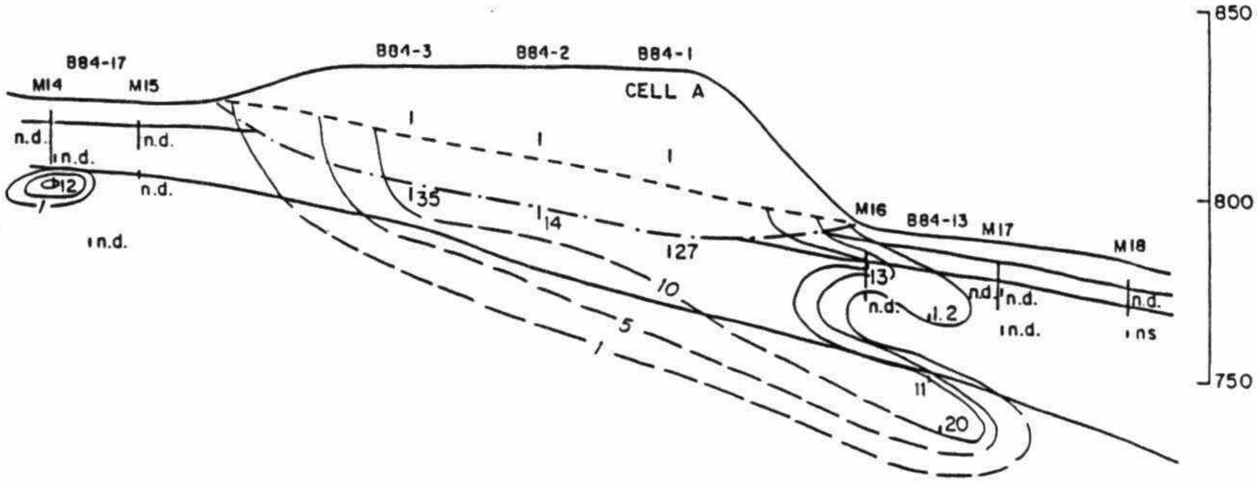

AUGUST 20, 1985 O-XYL

Figure 2.13 cont'd.

AUGUST 20, 1985 p/m - XYL



AUGUST 20, 1985 1,2,4 - TMB



The carbon tetrachloride (CCL4) plume (Figure 2.12) is more extensive than the trichloroethane (TCEA) or trichloroethylene (TCEY) plumes (Figure 2.13a and b). TCEY shows the greatest concentration decline along cross-section AA'. This is interpreted as greater biodegradation of TCEY compared to CCL4 or TCEA.

The volatile aromatic hydrocarbon distributions along cross-section AA' are also shown in Figure 2.13. The 1,2,4-trimethylbenzene (1,2,4-TMB) plume is the most unusual, having some of the highest concentrations in the lower clayey silt till, probably unrelated to landfill contamination. 1,2,4-TMB is a naturally-occurring compound. The toluene (TOL), p-plus m-xylenes (p/m-XYL) and 1,2,4-TMB plumes are the most restricted in the sand till. Ethylbenzene and o-xylene plumes are slightly more extensive. The o-xylene appears to have a rather high background level as it was found in almost all piezometers at 1 ug $L^{-1}$ or higher. The aromatic plumes appear to be more extensive, in general, than the halocarbon plumes.

Only the o-xylene plume is as extensive as the Cl plume and this appears to reflect background o-xylene problems rather than similar migrations. O-xylene is a naturally-occurring organic. The restriction of the organic contaminants is likely due to both sorptive retardation and biodegradation. Sorptive retardation alone is not the controlling process because relatively-higher sorbed and more retarded species have, in some cases, migrated as far as less retarded species. It appears that biodegradation must also have occurred, with the unexpected restriction of more-mobile organics, such as trichloroethylene and toluene, due to their preferred biodegradation within the leachate plume. Unfortunately, the uncertainty about inputs from the landfill and specific flow paths precludes a quantitative treatment of such processes.

### 2.4.5 Conclusions

Very few hazardous organics were found in leachate at the New Borden landfill site. Most organics of concern are either volatile halocarbons or volatile aromatics. Leachate appears to have migrated at least 150 m north from the oldest landfill cell which was operated from 1976 to 1979. Some trace organics also appear to have migrated this far, particularly carbon tetrachloride and perhaps ethylbenzene. Other volatile organics show a more restricted migration.

Retardation by sorption does not appear to be significantly limiting the mobility of the volatile chlorinated organics. Biodegradation appears to be the major limiting factor. Whereas carbon tetrachloride has migrated essentially as far as chloride, both 1,1,1-trichloroethane and trichloroethylene show less migration.

The aromatic hydrocarbon likely to be most restricted by sorptive retardation is naphthalene. It is restricted to within about 50 m of the landfill. The relative mobilities of the other aromatics do not fit a pattern expected based on sorptive retardation. Again biodegradation probably is the major factor restricting their mobility. Ethylbenzene and perhaps o-xylene appear to have migrated further than p/m-xylene, toluene, and 1,2,4-trimethylbenzene. It is suggested that the latter group are more biodegradable in the landfill leachate plume than ethylbenzene and o-xylene.

These observations and the interpreted biodegradations are consistent with an anaerobic leachate plume environment. However, extremely reduced methanogenic conditions probably only occur within the landfill. Less-reduced conditions seem to have permitted the persistence of some halocarbons off site. Conditions have not become aerobic however, because aerobic-degradable aromatics persist throughout much of the plume.

*Table 2.7*: New Borden Landfill Leachate Plume Organics Tentatively Identified by GC/MS Bracketed values are estimated concentrations as ug $L^{-1}$

*Volatiles*

Halocarbons

chloroform (25)
1,1,1-trichloroethane (12)
carbon tetrachloride (4)
trichloroethylene (22)
tetrachloroethylene (0.2)

Aromatic Hydrocarbons

benzene (25)
toluene (1390)
chlorobenzene (2.1)
ethylbenzene (50)
p/m-xylene (119)
o-xylene (56)
cumene (40)
1,2,4-trimethylbenzene (20)
napthalene (144)

*Phenols and Acids*

phenol
4-methylphenol
benzeneacetic acid
acid

$C_3$ to $C_{18+}$ fatty acids and various isomers or methyl esters

*Base/Neutrals*

2-hexanone
2-hexanol
d-fenchone

camphor
menthol
3-cyclohexanomethanol
1-isopropyl-4-methyl-cyclohexanol

2-methyl-cyclopentanol
4-propoxy phenol
dimethyl ester of phosphoric acid

N,N-diethyl-benzamide
1,2-benzenedicarboxylic acid, diethyl (?) ester

## 2.5 The Upper Ottawa Street Landfill Site

### 2.5.1 Introduction

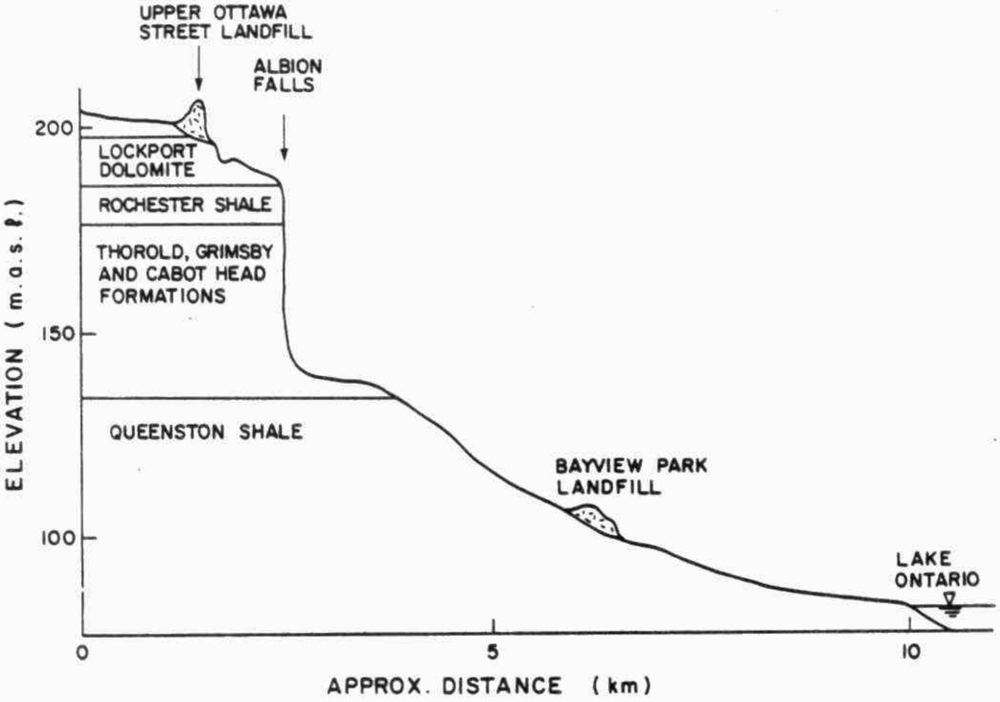
The Upper Ottawa Street landfill in Hamilton, Ontario received both municipal and industrial wastes from about 1954 to 1978. It occupies about 50 ha (1000 m by 500 m approximately). The landfill was established about 8 km from Lake Ontario upon hard cherty dolomite of the Silurian Lockport Formation at the edge of a plateu known as the Niagara Escarpment (Figure 2.14). The dolomite and shale bedrock comprises the same geological units that underly industrial landfills of concern in Niagara Falls, New York (Love Canal, Hyde Park, S Area, etc.). Besides normal municipal wastes, the Upper Ottawa Street site received liquid industrial waste which was burned and/or percolated via lagoons. From 1978 to the present the landfilled area has been covered with layers of sewage sludge, fly ash and a clay cover and vegetation encouraged.

The major pathway for groundwater flow in the area is via fractures. Observations at the Escarpment and from continuous drill core indicate the most abundant fractures are subhorizontal bedding plane features, but regular subvertical tensional fractures are apparently open, especially near the Escarpment. The hydrogeological studies are described by Cherry et al., (1984).

The geochemical studies of groundwaters in this area, attempted to define the extent of leachate impact on groundwater quality through various integrations of hydrogeochemical data with consideration of the site hydrogeology.

Sampled groundwaters were analyzed for a number of inorganic and organic parameters and for environmental isotopes, especially tritium ($^3H$). Additional analyses of landfilled materials obtained by coring, of surface waters near the site, and of seeps on the landfill were performed by other researchers. These helped define the contaminants emanating from the landfill. For groundwaters, up to 26 inorganic spec-

*Figure 2.14*: The location and geology of the Upper Ottawa Street landfill site.

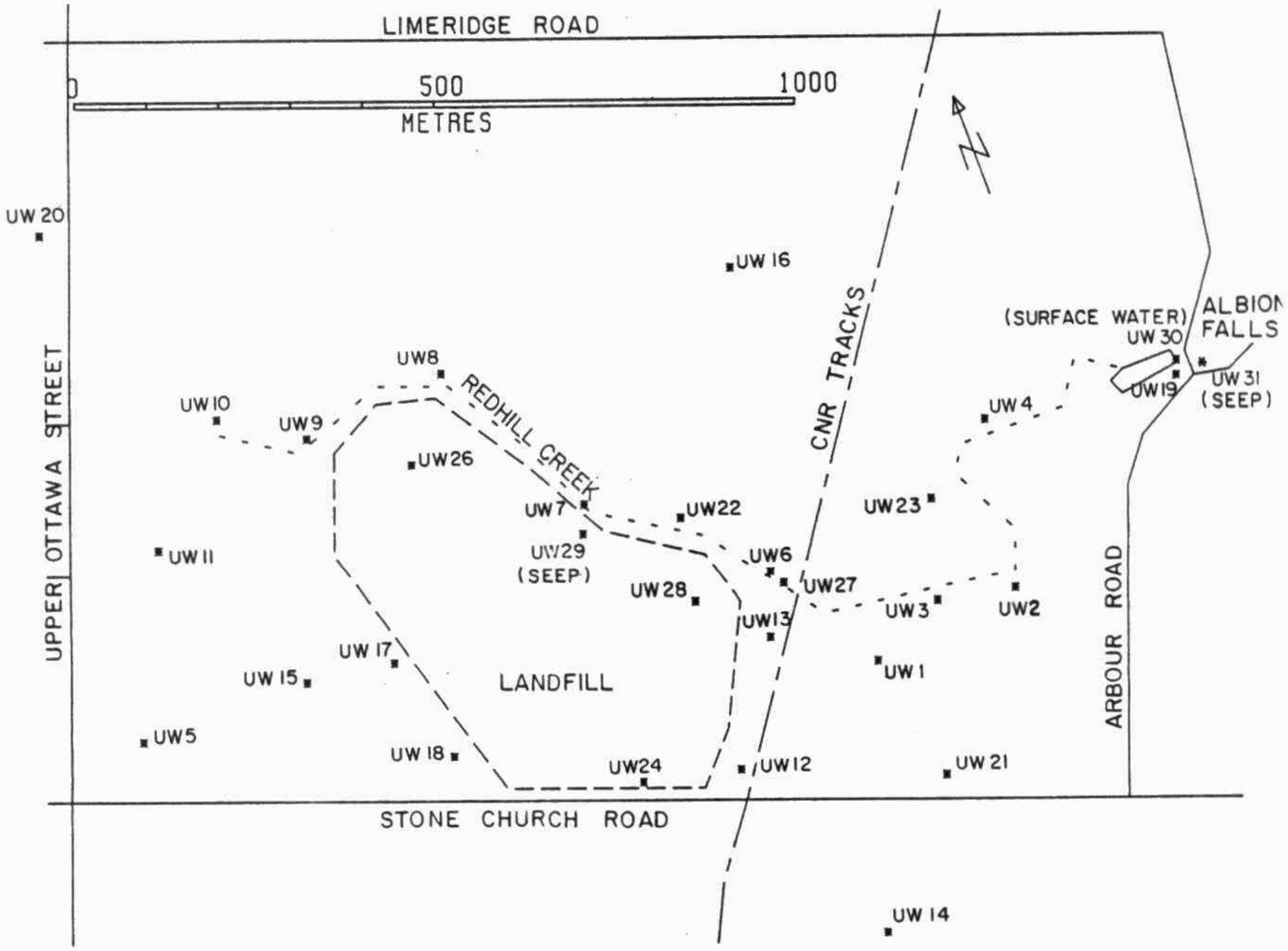


ies, indicator parameters (dissolved organic carbon, DOC, methane, $CH_4$) and 8 volatile hydrocarbons were routinely determined. Where sufficient water could be obtained, the approximate concentrations of about 60 additional volatile organics and of about 34 less volatile organics were determined. GC/MS methods were employed following either "purge-and-trap" or solvent extraction steps to concentrate and isolate the organics. Tritium analyses were used to draw inferences regarding the "age" or time since recharge of selected groundwaters.

Plumes of landfill-leachate contamination of groundwater in granular porous media appear to be regular and continuous (MacFarlane et al., 1983; Thurman et al., 1986; Robertson et al., 1985; Barker et al., 1986). In contrast, plumes in fractured rock appear less regular (Pankow et al., 1986). Since the Upper Ottawa Street site fell in the latter hydrogeological category, it was decided to provide a large number of groundwater sampling points to adequately establish the extent of groundwater contamination. The multilevel piezometers (Cherry and Johnson, 1982) provided a cost-effective means of sampling up to 6 specific, isolated depth intervals per borehole. The boreholes were continuously cored and the sampling intervals (1 to 2 m) were selected to correspond to fractured zones observed in this core. In all, 28 multilevel piezometers were established. Almost 100 intervals yielded water in quantities sufficient for monitoring of at least some chemical parameters. This is the most extensively instrumented landfill sited on fractured rock reported in the scientific literature.

The location of the landfill site and the piezometer network is shown in Figure 2.15. UW27 is angled from its surface location under the landfill at depth. UW26 and 28 are two 5 cm diameter PVC piezometers screened at two intervals just beneath the landfill. UW29 is a seep on the edge of the landfill; UW31 a small seep at the Escarpment. UW30 is a surface water sample from a pond of Redhill Creek just before the creek forms Albion Falls at the Escarpment.

*Figure 2.15*: The network of multi-level piezometers at the Upper Ottawa Street landfill site.



### 2.5.2 Piezometers and Sampling Protocol

Laboratory leachability tests were conducted with the materials used in the piezometers. A detailed description of these multilevel sampling devices is provided by Cherry and Johnson (1982). When the packers encasing Dowell (R) sealant maintained their integrity, minimal leaching of chemicals was found. However, if the rubber packers failed and Dowell (R) sealant came in contact with the water being sampled, significant organics were released to the water. Table 2.8 outlines these organics. Many of the chemicals shown in Table 2.8 could be derived from landfilled materials and would have made good leachate-impact indicators. Because of possible leaching from the piezometer installation, their usefulness as indicators was somewhat reduced.

Piezometer installations were hydraulically tested to identify leaking or failure of the packers. Suspect intervals were not included in subsequent monitoring. Chemical analyses of sampled waters were scrutinized for evidence of packer leakage. If concentrations of most of the dominant organics in Table 2.8 were found, packer leakage was suspected. If, for example, significant levels of benzothiozole but no diethylene glycol were found, the benzothiozole was considered to be in the groundwater.

Water standing in the piezometer was removed prior to sampling. Recommendations for adequate flushing, for example Gibb et al. (1981), are often arbitrary. Mackee (1983) monitored the changing groundwater chemistry during flushing of up to 12 volumes from piezometers at this site yielding at least 0.5 L $\text{min}^{-1}$. It is not clear from the results when (or if) stability of parameters such as Cl, pH, Eh or Fe, was obtained. Consequently, an arbitrary flushing of 2 piezometer volumes was adopted.

Many piezometer points yielded less than 0.1 L of water per minute. These were periodically flushed dry over 6 to 18 months, so that at least 0.5 and usually more than 2 piezometer volumes had been removed prior to the sampling reported herein.

Because of the limited availability of water from such piezometers not all parameters could be determined.

Multilevel piezometers were flushed and sampled using either a peristaltic pump or, where deeper water levels were encountered, a $N_2$-gas drive sampler described by Robin et al. (1982). The normal PVC piezometers (UW26 and 28) were sampled with a positive displacement bladder pump (Industrial and Environmental Analysts, Inc.). A major concern was the introduction of a negative bias in volatile organic data due to loss of volatile organics during sampling. Pankow (1986) and informal tests demonstrated that such bias is less than 10% for the reported volatile organics. Further details of sampling protocol and quality assurance tests are presented by Cherry et al. (1984).

### 2.5.3 Analyses

Analyses were performed by a number of laboratories with sufficient analyses of blanks, blind replicates and inter-laboratory comparisons to yield an excellent chemical data base. Details are provided in Cherry et al. (1984). Tables 2.9 to 2.11 indicate most of the parameters determined. The major inorganic species, electrical conductivity, nitrogen species and trace metals were determined by the Ontario Ministry of the Environment (MOE) using standard procedures. Total and dissolved organic carbon (TOC, DOC) was measured at Waterloo with a Dohrman DC 80 aqueous carbon analyzer. The volatile aromatic hydrocarbons were also determined at Waterloo by purge-and-trap GC methods.

At an early stage in this study a suite of samples was analyzed to determine both the volatile and the non-volatile organics present in groundwaters and leachate at this site. These were analyzed by the MOE trace organics laboratory and by M. Reinhard, Department of Civil Engineering, Stanford University. Waters were solvent extracted under basic then acidic conditions to yield the base/neutral and acid fractions which were subsequently analyzed by standard GC/MS techniques. Many compound identifications are tentative since no pure standards were processed and analyzed. Concentrations are only semi-qualitative for the same reason.

It was clear that few identifiable organics were both present at significant concentration in landfill leachate and absent in background groundwaters. It had been hoped that compounds such as volatile chlorinated hydrocarbons would provide excellent indicators of leachate occurrence in groundwaters. It was decided to emphasize the determination of volatile aromatics in subsequent monitoring because the GC analysis was cost-effective and these organics dominated the volatile organic fraction. Unfortunately, most of these organics occur in organic-rich sedimentary rocks (Tissot and Welte, 1978), so their mere presence in groundwaters cannot be used as proof of contamination. Additional GC/MS analyses of both volatile and extractable organics from selected groundwaters was conducted to provided additional tests of landfill-leachate contamination.

In order to substantiate both the volatile organic compound identification and quantitation, 11 groundwater samples were collected in quadruplicate with two duplicates analyzed by GC at Waterloo and two by GC/MS at Mann Testing Laboratories, Mississauga, Ontario. Purge-and-trap methods and chromatographic conditions were similar. For samples with highest volatile organic concentrations, some instances of co-elution were confirmed by GC/MS and so some of the high concentrations reported herein (determined by GC) are inflated. The GC results were shown to be reliable for lower concentrations (less than about 10 ugL$^{-1}$), where the results are most critical in identifying groundwaters where a minor leachate impact is possible.

### 2.5.4 Groundwater Geochemistry

Selected results of groundwater/seep/surface water analyses are presented in Tables 2.9 to 2.11. More complete data is available in Cherry et al. (1984). The landfill leachate chemistry is shown for leachate or highly leachate impacted groundwaters from UW26-1, UW28-2 and UW29-1. Leachate has a high total inorganic load (high electrical conductivity) reflecting high concentrations of Na, K, Mg, Cl and $HCO_3$ (alkalinity). This is common for landfill leachates (Robinson and Maris, 1979; Cherry, 1983; Baedecker and Back, 1979). The less-common, near-neutral pH and high alkalinity both probably results from dissolution of carbonate minerals by the initially acidic leachate. The leachate also contains high concentrations of dissolved organic matter (DOC), reduced nitrogen species (Kjeldahl N), Fe, F, and B. On the other hand, leachate is lower in Ca and oxidized sulphur ($SO_4$) and is almost free of oxidized nitrogen ($NO_3$). No dissolved oxygen, but up to 12 $cm^3$ of methane per litre of water were found. Trace metal concentrations are rather low, indicating either their low supply in the landfilled material (unlikely) or their immobility in the leachate. None of the metals (As, Cd, Pb, Se, Zn) form mobile, anionic or neutral inorganic species under the reduced, near-neutral leachate conditions (see Cherry et al., 1984).

In landfill leachate the aromatic hydrocarbons are commonly found at concentrations of 10 to 300 $ugL^{-1}$ (Table 2.9). Tables 2.10 and 2.11 indicate the lack of chlorinated organics in leachate at this site. This was not anticipated, given the history of liquid industrial waste landfilling. Unfortunately, this precludes the use of this normally-invaluable class of xenobiotic leachate indicators. This lack of chlorinated organics was also found in the analysis of solvent-extracted landfill material. This suggests that such compounds either were not landfilled, or were lost via volatilization, chemical reaction or biological transformation within the landfill. Certainly the strongly-reducing, methanogenic landfill conditions are favourable for microbially-mediated dechlorination reactors (Kobayashi and Rittmann, 1982).

Tritium ($^3H$) was found in leachate samples. This was anticipated since these waters must have been recharged since 1954 and these tritium levels would still be detectable today.

Excluding landfill leachates, the groundwater chemistry in this area is still extremely variable. It is possible to recognize two end-members as follows:

Type 1) recently-recharged (containing $^3H$), generally-shallow waters of low inorganic loading, and

Type 2) older (essentially no $^3H$), generally-deeper waters of high inorganic loading but with no definite indication of leachate contamination.

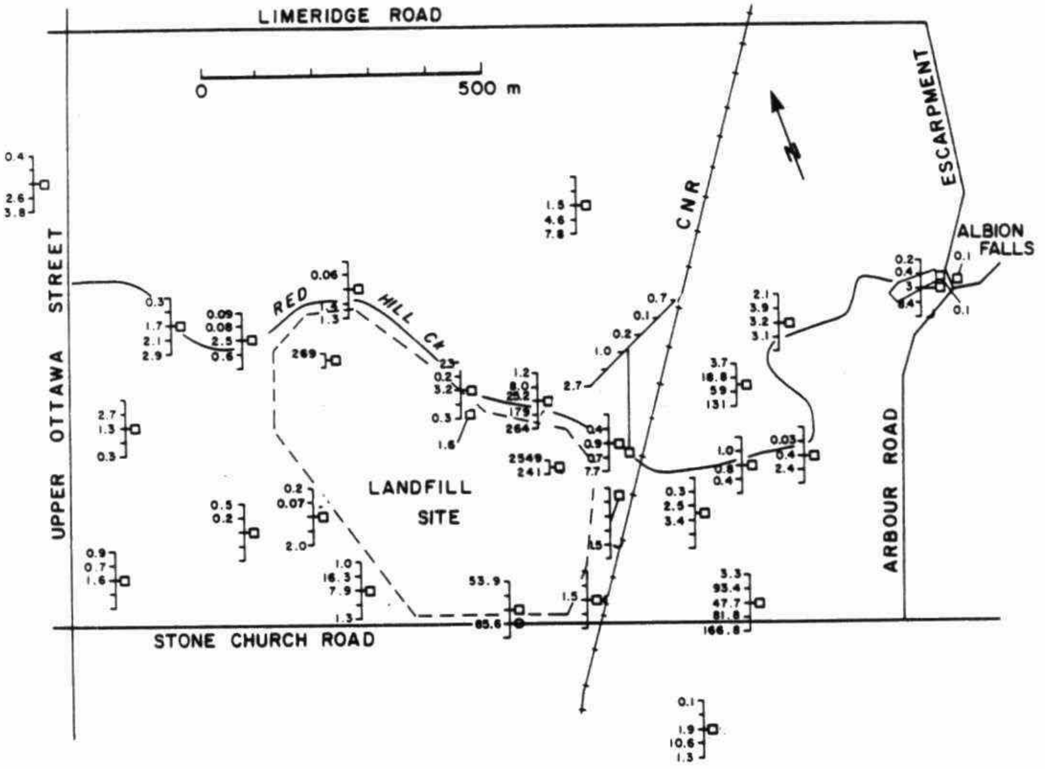
Typical type 1 and type 2 water chemistries are shown in Tables 2.9 to 2.11. Many intermediate waters may be some mixture of these two end members. They may also be intermediate in the chemical evolution over time, in which increased residence time permits more complete interaction with rocks producing a progressive increase in inorganic and organic loading.

The type 1 groundwaters contain traces of volatile aromatics, volatile hydrocarbons and volatile halogenated hydrocarbons (Table 2.9) which might represent atmospheric input in this industrial area. Traces of molecular sulphur, acenaphthene, nonanoic acid, and phenols were found, but they contain little else that cannot be attributed to contamination from piezometer materials.

Type 2 groundwaters often contained ug $L^{-1}$ levels of volatile aromatic hydrocarbons (Table 2.9), traces of molecular sulphur and significant concentrations of carboxylic and aromatic acids (Table 2.11). Other compounds present, such as solvents, phthalates and benzothiozole might be contaminants from the piezometer materials. Type 2 groundwaters appear to contain more identifiable organics, most of which are naturally-occurring petroleum hydrocarbons or acids which could be derived from their breakdown.

The distribution of solutes which could have a landfill origin was usually erratic in groundwaters at this site (Cherry et al., 1984). This is illustrated in Figure 2.16 for the aromatic hydrocarbon toluene. In this figure, the actual depth of the sampled interval is not indicated; rather, the relative depth is shown. Accurate depth information for each multilevel point is available in Cherry et al. (1984). In the multilevel piezometers, screened intervals are numbered sequentially from the shallowest. Leachate contained up to 2500 ug $L^{-1}$ toluene, while toluene ranged from less than 1 ug $L^{-1}$ to 170 ug $L^{-1}$ in groundwaters removed from the landfill site.

*Figure 2.16*: The distribution of toluene (ug $L^{-1}$) in groundwaters at the Upper Ottawa Street landfill site.



### 2.5.5 The Identification of Leachate-Impacted Groundwaters

It appears that there is no chemical parameter or group of parameters whose presence or ranges in concentration permit the unambiguous identification of all leachate-impacted groundwaters. This is because there was no indicator compound(s) unique to landfill leachate that was not present in uncontaminated waters nor in the piezometer materials that was practical to include in the analytical protocol for most groundwater. The extent of landfill-leachate in the groundwater is evaluated in the following s$^{-1}$tion by considering: 1) hydrogeological information about probable flow paths, 2) tritium data defining the time since recharge, and 2) chemical concentrations.

Considerable uncertainty is acknowledged in the identification of flow paths followed by landfill leachate fractured bedrock. Tritium is expected in landfill leachate since it must have been recharged after the landfilling began in 1954 and insufficient time has passed for radioactive decay to render the tritium level below detection. However, uncontaminated, recently-recharged type 1 groundwaters also contain tritium, so tritium alone is not a sufficient leachate indicator parameters. Also, where tritium-bearing leachate has dispersed into tritium-free type 2 groundwaters, dilution will be sufficient to render the tritium undetectable even where 10% to 25% of the groundwater is leachate.

The lack of chemical leachate indicators has been mentioned already. Dilution of the high leachate concentrations by dispersion into natural groundwaters also complicates the identification of weakly-impacted groundwaters.

Initially, a series of arbitrary tests were established. This was based upon a comparison of "background" groundwater chemistries (type 1 and 2) with leachate (Tables 2.9 to 2.11). The following observations are made:

1. leachate is intermediate in total inorganic load

2. Mg dominates Ca in leachate, Ca dominates Mg in background waters, leachate has the highest K/Mg ratio
3. leachate has the highest alkalinity, reduced nitrogen (Kjeldahl N), aromatic hydrocarbons and is high in DOC, B and Fe.
4. chlorobenzene occurs only in leachate samples, but not in all of these.

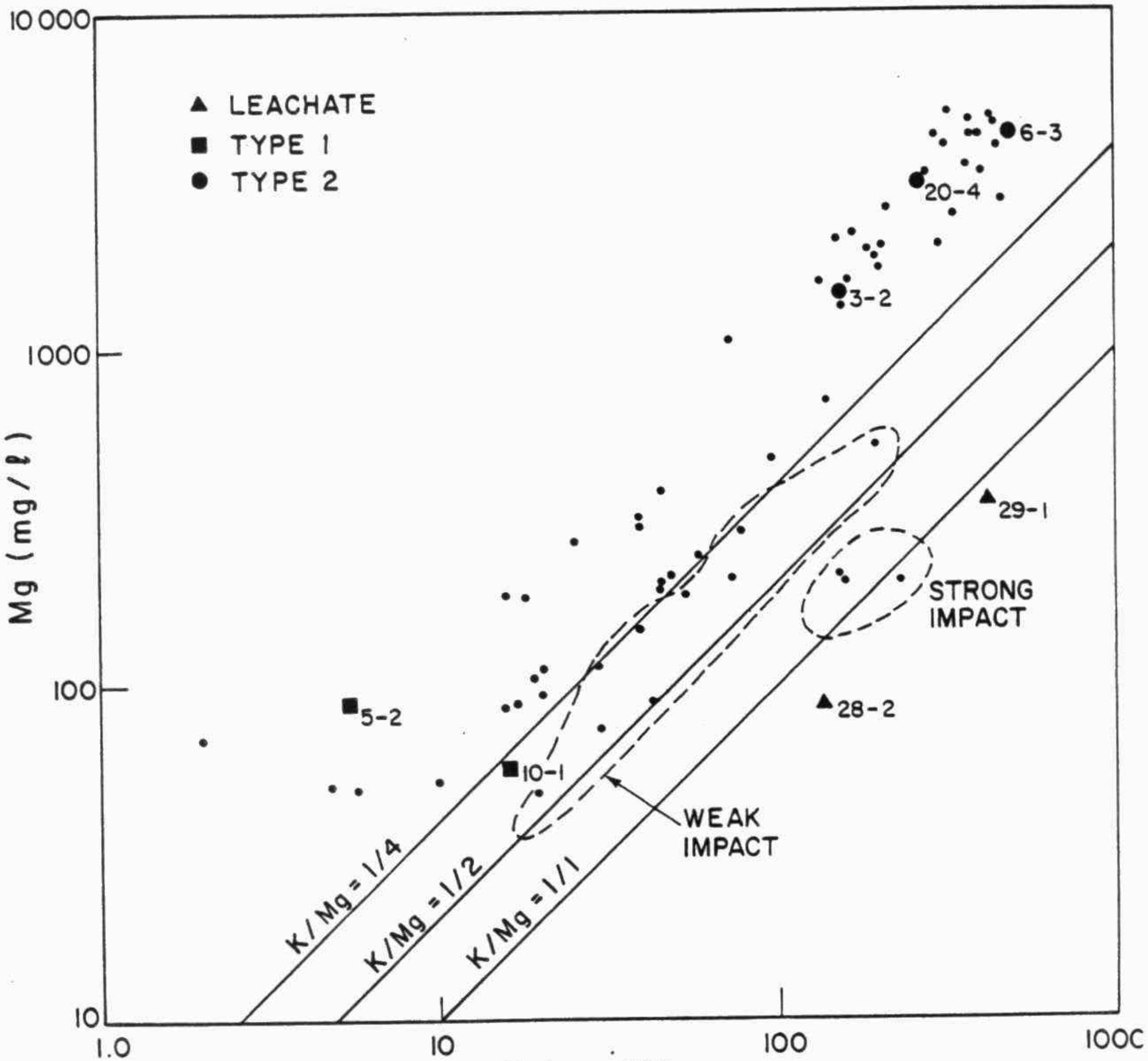
Fourteen tests for leachate impact were established (Barker et al., in prep.). For example, groundwaters plotting close to leachate samples in a Mg versus K cross-plot were scored as highly to weakly impacted based on their proximity. Figure 2.17 indicates this test.

Weak impact was valued as 0.5, strong impact as 1.0. The score for each groundwater was summed and then divided by the total possible score. Not all samples had sufficiently complete analyses to apply all criteria. The scores were tabulated as a percentage of the total possible score. The type 1 and 2 groundwaters listed in Tables 2.9 to 2.11 scored less than 14%. The leachate samples scored 54% to 68%. A score of 15% to 30% was arbitrarily accepted as weak evidence of leachate impact. A score of > 30% was accepted as indicative of a strong likelihood of leachate input. Of the 95 sampling points, 45 or 47% scored 15% or greater.

A number of statistical and pattern-recognition analyses were also performed on various subsets of the hydrogeochemical data to help identify those waters which are leachate-impacted. These analyses are described more fully by Barker et al. (in prep). They were employed because the data matrix in total is too large for visual inspection or elementary statistical analysis to reveal its structure.

Clearly, these statistical analysis cannot unequivocally define those groundwaters which are leachate-impacted. Rather, they highlight which groundwaters have significant chemical similarity to leachate. The results from the various data sets subjected to these analyses were reviewed and if a water was indicated as "contaminated" in

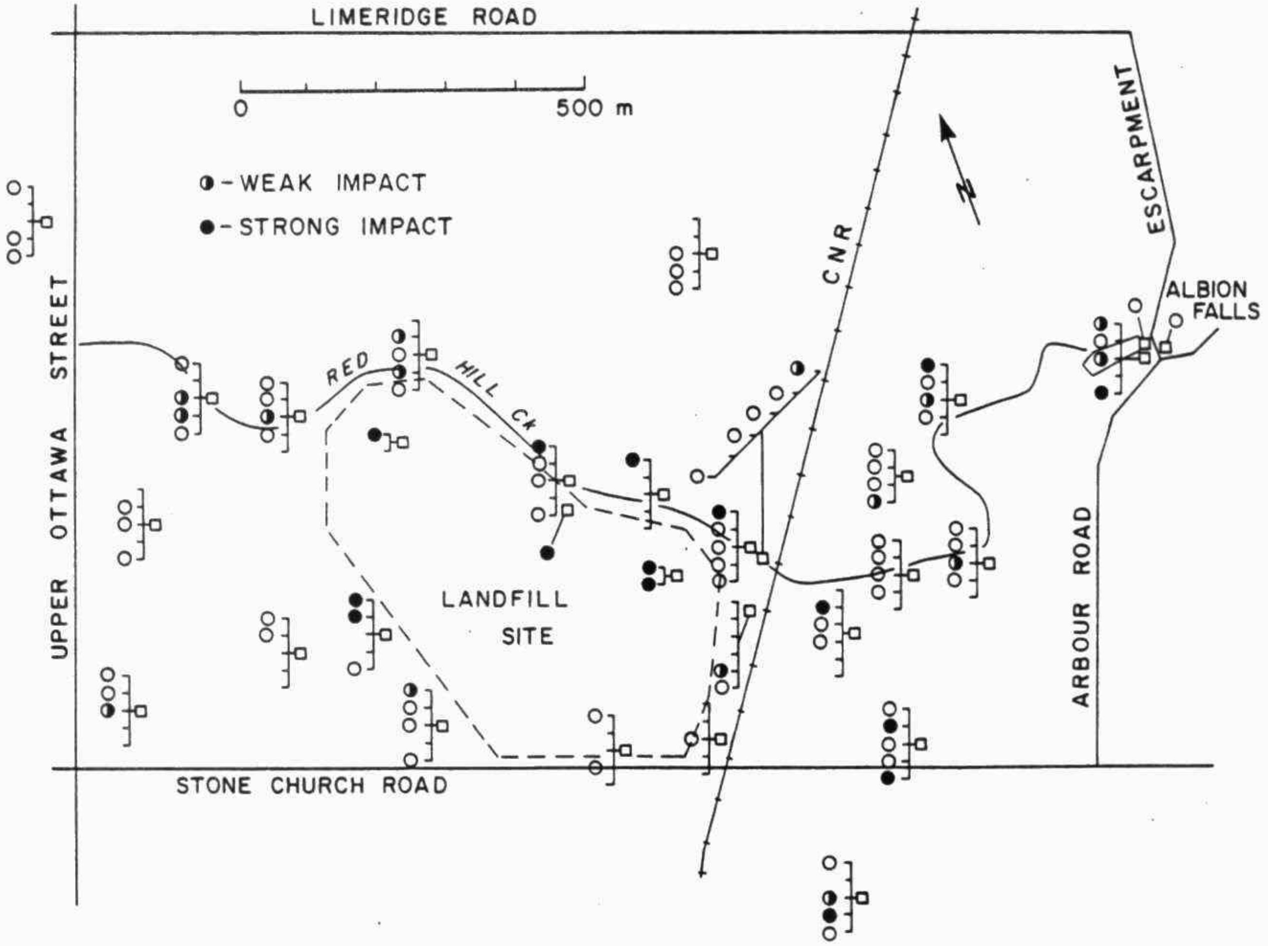
*Figure 2.17*: A cross plot of Mg and K concentrations (mg $L^{-1}$) in groundwaters at the Upper Ottawa Street landfill site.



more than 50% of the tests, it was designated as contaminated in the overall rating. Samples designated as highly likely contaminated were so indicated in most tests.

Considering the groundwaters indicated as leachate impacted in light of their position in the groundwater flow system leads to Figure 2.18 - the interpreted distribution of leachate-impacted groundwaters. Some waters which had a weak overall indication of leachate contamination, are not shown as contaminated in Figure 2.18. Designations were so changed because: 1) shallow groundwaters outside of the regional flow lines from the landfill are more likely impacted by local sources - flow lines from the landfill are difficult to imagine (piezometers 20-1, 05-1); 2) only arbitrary tests were applied and a slight, equivocal leachate contamination indicated (piezometer 03-1). Seep 31-1 is likely derived from the pond on Red Hill Creek near the escarpment and so is not directly impacted by groundwater pathways. It must be emphasized that the distribution is interpreted. There are no indicator parameters nor statistical tests to unequivocally divide the data set into contaminated and uncontaminated groups. However, by applying these various tests, considerably more confidence in the interpretations is generated.

*Figure 2.18*: The distribution of leachate-impacted groundwaters interpreted at the Upper Ottawa Street landfill site.



### 2.5.6 Conclusions

The impact of leachate from the Upper Ottawa Street landfill upon groundwaters is sporatic. The difficulty in recognizing unequivocal leachate impact probably reflects the lack of sensitive leachate indicator parameters and the very poor background water quality in the fractured sedimentary bedrock. In addition, the landfilled materials could have been relatively innocuous, or the leachate flow paths not intercepted by piezometers, or the leachate strength could have decreased rapidly many years ago. These latter possibilities are considered remote.

Recognition of leachate contamination in this situation was somewhat improved by the use of multivariate descriptive statistical analyses. These permitted simultaneous consideration of a broad range of parameters and was essential given the lack of practical, reliable specific leachate indicator parameters. Even so, the reliability of leachate impact identification is uncertain and cannot be expressed in terms of precise probabilities by these descriptive statistical analyses.

The migration of leachate within the fractured sedimentary bedrock flow system at this site appears to have produced an erratic, but restricted zone of contamination. Such leachate does not appear to have caused a major impairment in water quality given the poor quality waters present in the flow system. Most leachate contamination occurs within 100 m of the landfill boundary or to the east along the regional hydraulic gradient. The indication of leachate to the southeast of the site suggests leachate migration in this direction, perhaps along major fractured oriented southeast-northwest.

*Table 2.8*: Organic compounds identified in leaching of multilevel piezometer materials

| Organic | Relative Amount | Organic | Relative Amount |
|---|---|---|---|
| chloroform | 25 | octanoic acid | major |
| 1,1,1-trichloroethane | >10ppb | decanoic acid | major |
| carbon tetrachloride | n.d. | benzoic acid | major |
| 1,1,2-trichloroethane | p | benzothiazole | major |
| tetrachloroethane | p | benzothiazolethione | major |
| bromoform | p | tributyl phosphate | tr |
| benzene | p | phenyl ether | tr |
| trichloroethylene | n.d. | bis(2-ethylhexyl)phthalate | tr |
| toluene | p | diethylene glycol | major |
| chlorobenzene | n.d. | methyl carbitol | major |
| ethylbenzene | n.d. | salicylic acid | tr |
| xylenes | p | aniline | n.d. |
| chlorobenzenes | n.d. | acenaphthene | n.d. |
| naphthalene | tr | flouranthene | n.d. |
| phenol | tr | di-n-butyl phthalate | major |
| cresol | tr | | |

n.d. - not detected
tr - below quantitation
p - present but not qualified
major- a major peak on GC

*Table 2.9*: The geochemistry of leachate, type 1 and 2 groundwaters - routine monitored parameters

| Parameter | Leachate | | | Type 1 | | | Type 2 | | |
|---|---|---|---|---|---|---|---|---|---|
| | 26-1 | 28-2 | 29-1 | 5-1 | 10-1 | 19-1 | 3-2 | 16-3 | 20-4 |
| pH | | 7.86 | 7.67 | 7.31 | 6.98 | 7.02 | 6.70 | 6.06 | 6.61 |
| Cond (uS) | | 25900 | 13100 | 1520 | 3000 | 3800 | 64000 | 150000 | 108000 |
| Ca (mgL$^{-1}$) | | 19.0 | 87.5 | 140 | 545 | 334 | 5500 | 16400 | 10300 |
| Mg | | 86.0 | 355 | 50.0 | 57.0 | 110 | 1460 | 4300 | 3050 |
| Na | | 4700 | 2120 | 108 | 161 | 310 | 8700 | 29400 | 15100 |
| K | | 135 | 408 | 4.8 | 16.3 | 19.8 | 156 | 490 | 267 |
| Cl | | 4360 | 3190 | 182 | 202 | 710 | 27300 | 84600 | 52400 |
| Alk. (as $CaCO_3$) | | 9130 | 3540 | 247 | 251 | 407 | 298 | 45.0 | 107 |
| $SO_4$ | | 130 | 40.0 | 273 | 1360 | 645 | 1330 | 1080 | 1150 |
| F | | 6.6 | 1.3 | 1.2 | 0.8 | 0.4 | | | |
| $NO_3$ (as N) | | 0.5 | 0.3 | 0.2 | < 0.1 | < 0.1 | 0.4 | < 0.1 | 1.1 |
| Kjeldahl N | | 1600 | 380 | < 0.3 | 5.0 | 2.5 | | 65.0 | 45.0 |
| B | | 120 | 24.0 | 0.21 | 0.8 | 0.7 | 10.0 | 3.2 | 6.9 |
| Fe | | 7.1 | 3.2 | 0.68 | 0.6 | 2.0 | 0.24 | 0.88 | 3.1 |
| Mn | | 0.16 | 0.20 | 0.14 | 0.05 | 0.45 | 0.35 | 1.1 | 1.3 |
| As | | 0.029 | 0.003 | 0.001 | <0.001 | <0.001 | 0.001 | <0.001 | 0.001 |
| Cd | | < 0.010 | <0.005 | <0.002 | <0.005 | 0.0008 | 0.005 | <0.005 | <0.002 |
| Pb | | 0.097 | 0.032 | 0.015 | 0.03 | <0.003 | <0.030 | 0.09 | <0.030 |
| Se | | 0.004 | 0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Zn | | 0.47 | 0.028 | 0.11 | 0.009 | 0.15 | 0.06 | 0.04 | 0.060 |
| DOC | | 4600 | 294 | 2.8 | 32.9 | 3.4 | 100 | 4.2 | 37 |
| Tritium (T.U.) | | | 129 | | 62 | 88 | n.d. | 4 | 1 |
| Benzene (ugL$^{-1}$) | 14.2 | 27.0 | 8.9 | 0.06 | 0.01 | n.d. | 1.0 | 0.8 | 0.7 |
| Toluene | 269 | 242 | 1.6 | 0.9 | 0.3 | 0.2 | 1.0 | 1.5 | 2.6 |
| Chlorobenzene | 107 | n.d. | 5.2 | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| Ethylbenzene | 75.7 | 74.0 | 18.1 | 0.4 | n.d. | n.d. | 0.2 | 0.1 | 0.2 |
| p-Xylene | 76.3 | 191 | 12.5 | 1.8 | 0.03 | 0.07 | 0.5 | 0.1 | 0.7 |
| o-Xylene | 30.8 | 123 | 53.1 | 0.5 | n.d. | n.d. | 0.4 | 0.1 | 0.3 |
| Cumene | 2.8 | 4.2 | 2.3 | n.d. | n.d. | n.d. | 0.02 | n.d. | n.d. |
| 1,2,4-Trimethylbenzene | 18.4 | 50.8 | 2.3 | 0.6 | 0.03 | 0.03 | 0.3 | 0.1 | 0.5 |
| Naphthalene | 132 | 60.3 | 10.7 | 0.4 | 0.04 | n.d. | 2.0 | 0.1 | 0.3 |

n.d. - not detected

*Table 2.10*: The geochemistry of leachate, type 1 and type 2 groundwaters - volatile organics determined by GC/MS (ug $L^{-1}$)

| | *Leachate* | | *Type 1* | | *Type 2* |
|---|---|---|---|---|---|
| | 28-2 | 29-1 | 10-1 | 19-1 | 16-4 |
| Dichloromethane | n.d. | 4.8 | n.d. | n.d. | n.d. |
| Chloroform | 1.0 | 1.5 | tr | 0.6 | n.d. |
| 1,1,1-Trichloroethane(a) | n.d. | 0.1 | m | n.d. | n.d. |
| Chloroethylene | m | n.d. | n.d. | n.d. | n.d. |
| 1,2-Dichloroethylene | 10 | n.d. | n.d. | n.d. | n.d. |
| Acetone | 1.4 | s | n.d. | 2.0 | n.d. |
| 2-Butanone | 2.6 | n.d. | n.d. | 1.1. | n.d. |
| Camphor | n.d. | s | n.d. | n.d. | n.d. |
| Tetrahydrofuran(a) | 24 | s | m | 6.0 | n.d. |
| 1,4-Dioxane | 27 | s | n.d. | n.d. | n.d. |

n.d. - not detected
tr - trace (<1% of total detector response)
s - significant (1to10% of total detector response) but not quantified
m - major (>10%of total detector response) but not quantified
a - detected in leach test of piezometer material (Table 2.8) or reported in PVC glue

*Table 2.11*: The geochemistry of leachate, type 1 and type2 groundwaters - extractable organics determined by GC/MS

| | *Leachate* | | *Type 1* | | *Type 2* | |
|---|---|---|---|---|---|---|
| | 28.2 | 29.1 | 10-1 | 19-1 | 20-4 | 20-5 |
| Benzothiazoles(a) | m | tr | tr | s | n.d. | tr |
| 1,2,4-Trithiolanes(a) | n.d. | n.d. | n.d. | n.d. | n.d. | tr |
| Anilines | n.d. | tr | n.d. | n.d. | n.d. | n.d. |
| Phthalates(a) | s | s | tr | tr | tr | tr |
| PCBs | tr | n.d. | n.d. | n.d. | n.d. | n.d. |
| Molecular S($S_8$) | m | n.d. | n.d. | tr | n.d. | tr |
| Pentanoic acid | n.d. | n.d. | n.d. | n.d. | --- | s |
| Hexanoic acid | tr | n.d. | n.d. | n.d. | --- | m |
| Octanoic acid(a) | tr | n.d. | n.d. | n.d. | --- | s |
| Benzoic acid(a) | tr | tr | tr | n.d. | --- | tr |
| Salicylic acid(a) | n.d. | n.d. | n.d. | n.d. | --- | m |
| Phenols(a) | s | tr | n.d. | tr | --- | n.d. |

n.d. - not detected
--- - not determined
tr - trace (see Table 2.10)
s - significant (see Table 2.10)
m - major (see Table 2.10)
a - detected in leach test (Table 2.8)

## 2.6 Tricil Site

### 2.6.1 Site Hydrogeology

With the support of an NSERC Strategic Grant, an investigation of contaminant migration beneath a completed disposal cell has been conducted. The waste disposal facility, which is operated by Tricil Limited, is located 15 km southwest of Sarnia, Ontario. It is the only landfill in Ontario that receives hazardous wastes exclusively. We selected the site for this study primarily because the natural clay deposit is thick and therefore vertical boreholes through the waste could be drilled a metre or two into the clay without destroying the integrity of the overall deposit. The clay deposit extends 25 m from the bottom of the waste to the bedrock aquifer underlying the clay. The site possesses additional attributes, such as waste material that offers no obstructions to drilling, accurate information on the locations and depths of old cells, and hydrogeological conditions that have been determined in detail in previous investigations. A more detailed discussion of our studies can be found in Appendix D.

The waste-disposal cell selected for this investigation was excavated in 1979. The cell received its final load of waste in 1980. The waste mass consists mainly of fly ash from a nearby coal-fired electrical generating station. Liquid hazardous wastes (chemical composition unspecified) were mixed with the fly ash prior to disposal. The cell has a 2 m thick cover of compacted clay.

The study site is situated on a flat clay plain that extends more than 20 km in all directions from the site. The clay deposit which is late Quaternary in age, was formed by glaciers that protruded into a large glacial lake. The deposit contains numerous small pebbles and granules of shale bedrock indicative of the glacial-till origin of the deposit. About 40% of this glacial till is clay-sized particles, which are primarily illite and chlorite (Quigley and Ogunbadejo, 1976). The remainder consists of silt and sand-sized material and a small percent of pebbles.

Desaulniers et al. (1981), and Desaulniers and Cherry (1986) have studied the permeability of the clay, and the flow rates and age of groundwater in the clay at several locations on the clay plain including the Tricil site. The investigations concluded that, below about 5 m from ground surface, the clay is unweathered, has an average hydraulic conductivity less than 5 x $10^{-9}$ cm $s^{-1}$, has downward groundwater flow at average linear velocities less than several millimetres per year, and contains water that is very old, generally many thousands of years old. They also concluded that natural solutes in the groundwater, such as $Cl^{-1}$, $Na^+$, $^{18}0$ and $^2H$ have developed vertical concentration profiles dominated by the influence of molecular diffusion during geologic time. Desaulniers et al. (1986) simulated the vertical concentration profiles by means of one-dimensional diffusion models and diffusion times of 9,000 to 16,000 years.

From analyses of core samples taken from weathered clay at the bottom of a municipal landfill in Sarnia, Goodall and Quigley (1977) and Crooks and Quigley (1984) determined vertical profiles of several inorganic leachate-derived constituents. While the data suggest diffusion as the dominant cause of profile development, they only had limited success in the fitting of a diffusion model to the data. Our investigation has some similarities to the work done by Quigley and co-workers, but our focus is on the clay at greater depth where it is unweathered and on organic compounds rather than inorganic compounds other than chloride.

### 2.6.2 Sampling, Analyses and Results

After sectioning the cores, pore water obtained by squeezing numerous core segments was analysed for chloride and for volatile organic compounds by standard purge-and-trap GC/MS methods (Appendix D). The compounds found at highest concentrations were aromatics and some volatile halocarbons (Table 2.12). Chloride was detected in the clay to a maximum depth of 83 cm below the bottom of the waste.

The most mobile organic compounds (benzene, dichloropropane) were found only to a depth of about 15 cm and there at greatly reduced concentrations (Appendix D). Although there is a large downward hydraulic gradient in the clay, the downward migration of chloride is caused only by molecular diffusion without significant influence by advection. The smaller distances of penetration for the volatile organic compounds are attributed to adsorption although biotransformation may play a role as well. The studies at this site are continuing.

### 2.6.3 Conclusions

Because the clay deposit is 20 m thick, it will take thousands of years for contaminants to diffuse through the clay into the underlying aquifer. If biotransformation occurs, at least some contaminants may never reach the aquifer. This study also has implications with respect to low-permeability clay liners used at waste disposal sits. The results of this study suggest that for liners of typical thickness ($< 1$ m), molecular diffusion will cause breakthrough of relatively mobile organic contaminants in several years or less.

*Table 2.12*: Selected organics and chloride in pore waters at the Tricil site. Concentration of chloride is in mg $L^{-1}$ and organics are in ug $L^{-1}$ (from core 1, Johnson et al., 1986).

| Solute | Distance Below Landfill Cell (cm)<br>-15.2 to -7.6 | <br>0.0to 7.6 | <br>22.9 to 30.5 |
|---|---|---|---|
| Chloride | 1410 | 1080 | 664 |
| Benzene | 7920 | 283 | 4[a] |
| Toluene | 9520 | 470 | 9[a] |
| Ethylbenzene | 3320 | 72.9 | 0.8[a] |
| Naphthalene | 2350 | 23.9 | 0.1[a] |
| Trichloroethane | 844 | 32.7 | 0.4[a] |
| 1,2-Dichloropropane | 821 | 39.2 | 0.3[a] |

a - less than the method detection limit so result is only qualitative

## 3

# OVERVIEW OF ORGANIC CONTAMINANT OCCURRENCE AND MIGRATION

## 3.1 Organics Occurring in Landfill Leachate Plumes

The dominant organics found in leachate plumes emanating from the six landfills are summarized in Table 3.1. The organic acids were dominant, resulting from the anaerobic breakdown of organic refuse. The most significant contaminants were halocarbons and volatile aromatic hydrocarbons including benzene, toluene, xylenes, chlorobenzenes and other substituted benzenes. Other commonly detected compounds included non-chlorinated solvents such as acetone, tetrahydrofuran and 1,4-dioxane. These were usually less abundant than the halocarbons and aromatics. Significant occurrences of most other organics on the EPA's priority pollutant list were rare. Either these were not significant components leaching from the refuse or they did not persist into the leachate-impacted groundwaters. However, it must be remembered that exhaustive leachate characterization was not the objective of this study and so some organics of specific concern might not have been identified. Many organic components (GC/MS peaks) were not identified at each site.

The lack of significant organic contaminants in the groundwater contaminated by the Borden landfill is probably due to the nature of most of the landfilled refuse (building material, little industrial material) and to the periodic refuse burning. Other municipal landfills in sandy or sandy till deposits (North Bay, Woolwich and New Borden) are releasing more organic compounds and at higher concentrations into the groundwater. Some organics found at the Woolwich site could have had an industrial waste origin, but generally the organics found could be derived from household waste. Landfills installed upon fractured sedimentary bedrock (Bayview Park and Upper Ottawa Street) were the most likely to have received significant industrial waste with the latter certainly having received considerable liquid industrial material. However, the same halocarbons and aromatics dominated the organic spectrum at these sites, perhaps with a few more chlorinated benzenes found in the Bayview Park leachate-impacted groundwater (Pankow et al., 1986). Surprisingly, the groundwater from the Upper Ottawa Street site did not indicate significantly more organic contaminants due to the industrial disposals at this site.

At none of the sites were the concentrations of halocarbons or aromatics found in leachate-impacted groundwaters that were entering surface waters or were approaching water supply wells cause for immediate action. Other organics such as phenol and some inorganics may be cause for action. Natural attenuation has reduced concentrations of the target organics to below most drinking water guidelines or limits before wells or surface discharge is encountered. Concentrations of most individual organic contaminants typically determined in these studies (EPA priority pollutants) were usually less than 100 ug $L^{-1}$. Acidic products of refuse degradation were commonly present in the mg $L^{-1}$ to 1000 mg $L^{-2}$ range, except at the Borden landfill where all contaminants were present at lower concentrations. The similarity of organics in leachate at these municipal sites must reflect the overall similarity in municipal refuse and the lack of significant volumes of industrial organics co-disposed. Even at the Tricil site, the more mobile organics were the same monoaromatics and halocarbons.

## 3.2 Organic Contaminant Migration and Persistence

Studies at these seven landfill sites emphasized those organics which were

1. at high concentration in leachate,
2. of possible environmental concern,
3. relatively simple to determine quantitatively,
4. likely to be mobile in soils and groundwater

Inevitably, the halocarbons and volatile aromatics were selected. After relatively innocuous organic acidics, these were usually present at highest concentrations in leachate (Table 3.1). These groups included most of the EPA priority pollutants found in leachate. Rapid, quantitative analytical methods were developed to permit the determination of their distribution in some detail in contaminant plumes. Because of their rather high water solubilities, all in excess of tens of mg $L^{-1}$, these compounds should readily enter leaching waters and could be among the most rapidly migrating in groundwaters.

All leachate-derived solutes were found to undergo significant dilution or attenuation as they migrated from the landfills. Table 3.2 illustrates this by examining the concentrations of selected contaminants near the landfill and comparing these to concentrations along the groundwater flow path from the site. Much of the observed decreases in concentration must be attributed to the process of *dispersion* - the mixing of leachate and background groundwater that occurs throughout the solute transport domain. The extent of such dispersive dilution was estimated from the decrease in concentration of a solute like chloride which undergoes no other dilution process. For organic contaminants, two other processes can also bring about lower concentration. *Sorption*, essentially by solid organic matter in aquifer material can both lower the solution concentration and retard the migration of sorbing solutes by causing them to spend some time in the static, sorbed state during their advection in groundwater.

*Table 3.1*: The approximate maximum concentration (ug $L^{-1}$) of selected organic contaminants found in leachate-contaminated groundwaters at six landfill sites. Many concentrations are only approximate.

| Contaminant | Landfill Sites | | | | | |
|---|---|---|---|---|---|---|
| | Borden | Woolwich | North Bay | New Borden | Upper Ottawa Street | Tricil |
| Aliphatic, aromatic and carboxylic acids | 20 | >10,000 | > 300 | | >1000 | - |
| carbon tetrachloride | <1 | 5 | <1 | 9 | p | n.d. |
| chloroform | <1 | 20 | <1 | 25 | 5 | n.d. |
| trichloroethylene | 1 | 37 | 2 | 750 | p | n.d. |
| trichloroethane | n.d. | 7 | <1 | 90 | 20 | 844 |
| tetrachloroethylene | n.d. | 2 | <1 | <1 | <1 | n.d. |
| acetone | <1 | - | 6 | - | 6 | - |
| tetrahydrofuran | p | - | 9 | - | 200 | - |
| 1,4-dioxane | n.d. | - | <1 | - | p | - |
| benzene | 3 | 70 | 51 | 50 | 60 | 7920 |
| toluene | 1 | 7500 | 60 | 1400 | 2600 | 9520 |
| xylenes | <1 | 700 | 140 | 500 | 3500 | - |
| ethylbenzene | <1 | 1100 | 64 | 120 | 700 | 3320 |
| 2,4-,2,4-trimethylbenzene | n.d. | 10 | 250 | 70 | 450 | - |
| chlorobenzene | n.d. | n.d. | 105 | n.d. | 110 | - |
| dichlorobenzenes | <1 | n.d. | 13 | n.d. | 5 | - |
| naphthalene | n.d. | 50 | 15 | 260 | p | 2350 |
| phenols | - | 1100 | 10 | p | p | - |
| benzothiozoles | <1 | 30 | 10 | n.d. | p | - |
| PAH's | - | - | n.d. | - | n.d. | - |
| phthalates | <1 | p | 110 | p | p | - |

p: detected but concentration not estimated
n.d.: not detected
- : not determined

The second additional attenuating process is *biotransformation* or *biodegradation* Microbes convert the organic compound to simple inorganic molecules such as $CO_2$, $H_2O$ or $CH_4$ usually, but this conversion may be to other organic molecules under some conditions. Chemical transformations such as hydrolysis or reductive dechlorination are also possible, but, for the organics emphasized in this study, the major transformation is though to be microbial.

In the very permeable sand aquifers at North Bay and Woolwich, dispersion seems to have brought about a very significant dilution (10 to 100-fold decreases) of all leachate parameters over the 800 m to 1000 m travel distances found at these sites. For the North Bay site, Table 3.2 indicates chloride attenuation of 30% and organic contaminant attenuation of 46% to more than 94% over the initial 340 m of the groundwater flow. The halocarbons and volatile aromatics seem to have undergone even greater attenuation than chloride, attributed mainly to biotransformation reactions.

At the more-recently established New Borden site on less-permeable sandy till, some organics seem to have migrated as far as chloride has (about 150 m) while others show a much more restricted distribution, again attributed to biotransformations rather than to sorptive retardation. Table 3.2 indicates that, while chloride attenuation due to dispersion brings about a 79% decrease in chloride concentrations, the organic contaminants undergo more dilution, and for some essentially complete attenuation. Since some organics have migrated almost as far as chloride, they must be very mobile in general at this site. Such high mobility of the volatile aromatics and halocarbons was expected, based on the properties of these organics and the very low sorptive potential of the low organic carbon sands, gravels and sandy till at the North Bay, Woolwich and New Borden sites.

The distribution of contaminants at the landfill sites on fractured sedimentary rocks - Bayview Park and the Upper Ottawa Street sites - is much more complex and

*Table 3.2*: The approximate decrease in contaminant concentrations from near the landfill to some distance along the groundwater flow system.

| Landfill Site | Contaminant | Initial Conc. (ug $L^{-1}$) | Flow Distance (m) | Observed Conc. (ug $L^{-1}$) | % Decrease |
|---|---|---|---|---|---|
| Woolwich near ML4 to ML-16 | chloride | 400 | 160 | 46 | 89 |
| | trichloroethylene | 15 | 160 | 1.7 | 89 |
| | 1,1,1-trichloroethane | 8 | 160 | 6 | 25 |
| North Bay Near G to near LL | chloride | 330 | 340 | 230 | 30 |
| | benzene | 28 | 340 | 13 | 54 |
| | toluene | 19 | 340 | <1.2 | >94 |
| | chlorobenzene | 35 | 340 | 19 | 46 |
| | ethylbenzene | 60 | 340 | 31 | 48 |
| | p/m-xylene | 85 | 340 | 15 | 82 |
| | o-xylene | 24 | 340 | 3.7 | 85 |
| | 1,2,4-trimethylbenzene | 65 | 340 | 17 | 73 |
| | naphthalene | 21 | 340 | 10 | 52 |
| New Borden B84-2 to M-18 | chloride | 549 | 150 | 115 | 79 |
| | carbon tetrachloride | 8.5 | 150 | 1.2 | 86 |
| | trichloroethylene | 9.4 | 150 | <0.1 | >99 |
| | 1,1,1-trichloroethane | 7 | 150 | 0.2 | 97 |
| | toluene | 747 | 150 | <0.5 | >99 |
| | ethylbenzene | 113 | 150 | 3.7 | 97 |
| | 1,2,4-trimethylbenzene | 14 | 150 | <1.0 | >93 |
| | naphthalene | 154 | 150 | <1.0 | >99 |

consequently difficult to interpret in terms of organic solute migration and persistence. At the Upper Ottawa Street site, the highest concentrations of halocarbons and volatile aromatics are restricted to within 50 m of the sites themselves. Beyond this immediate vicinity, organic contaminants were found at much lower concentrations and sporatically. The distributions are complex, in part due to poor background quality (high Cl, traces of aromatics), possible additional disposal in the vicinity of the landfill, and the uncertainty of transport in discrete fractures rather than through connected pore spaces. For whatever reasons, significant levels of individual organic contaminants ($>$ 10 ug $L^{-1}$) are not found beyond about 100 m from this landfill site. Again, attenuation due to dispersion and biotransformations are though to be the processes limiting organic contaminant transport.

In the impermeable clayey till at the Tricil site, molecular diffusion appears to be the dominant contaminant transport process. Attenuation of mobile organics is significant and is attributed to sorptive retardation.

Biotransformations appear to be a dominant control over the behaviour of halocarbon and volatile aromatic contaminants in these landfill leachate plumes (Tricil situation excepted). This reflects, in part, the variety of microbial environments present. Each environment probably has unique biotransformation potentials. Where significant organic loading to the leachate occurs (all but Borden landfill) the initial environment is likely extremely anaerobic. This promotes methanogenic bacteria which have excellent potential to biotransform halocarbons (Wilson and McNabb, 1983) but only a minor potential to biotransform volatile aromatics (Wilson et al., 1986). As dispersion mixes in more oxidized groundwaters, less-strongly reducing conditions develop, with perhaps more potential to biotransform aromatic structures. In some leachate plumes (Woolwich, perhaps New Borden), aerobic conditions may temporarily exist in the distal portions where leachate mixes with large ratios of oxygenated, natural groundwaters. In such an environment, aerobic bacteria can be expected to rapidly biotransform aromatics. In addition, if methane from the landfill also enters this initially - aerobic zone, then methane-oxidizing aerobes may operate. This group of bacteria has been shown to rapidly biotransform some halocarbons (Wilson et al., 1985). Thus, the organics from landfill leachates can encounter various environment of different biotransformation potential during transport. This provides at least the potential for a variety of biotransformations to occur. It is not surprising, therefore, that some evidence for biotransformation of halocarbons and volatile aromatic contaminants is found within six of the seven leachate plumes investigated. This may be the major safeguard in the groundwater environment that will continue to limit the environmental impact of mobile organic contaminants in these sanitary landfill leachates.

## 3.3 Limitations and Recommendations

The mobility and persistence of organic contaminants in seven landfill leachate plumes has been evaluated by determining the distribution of selected organic contaminants in the affected groundwaters. The accuracy or reliability of the inference of mobility and persistence is limited by the hydrogeological complexity of each site. which is worst for the sites on fractured rock (Bayview Park and Upper Ottawa Street). It is also limited by temporal variability in the organic solute inputs from the landfill and resultant variability observed along the flow systems. Thus, an apparent decrease in solute concentration along a plume might reflect, in part at least, a change in the input concentration from the landfill over time. An interpretation of the observed distribution might attribute such a decreasing concentration to biodegradation or dispersive dilution, when it could be, in part, a result of temporally variable inputs from the landfill.

The likelihood of this misinterpretation is minimized by sampling the leachate plume many times over the study and by obtaining adequate hydrogeological information about each site. However, even for the well-characterized North Bay site, some uncertainty in the resultant interpretation remains. Thus, rates of biotransformation or of dispersive dilution have not been presented - their values being too uncertain. We are left with good but not conclusive evidence that such processes are controlling the organic contaminant distribution.

This is still a very useful result because it deals with real leachate plumes, not laboratory systems whose representativeness must always be questioned. We can conclude that the migration of serious concentration of many organic contaminants is limited by dispersive dilution and biotransformations in sanitary landfill leachate plumes. Unfortunately, we have no specific process rates which would be useful in predictions for other contamination situations.

In order to obtain such process rates, we feel that controlled field injection experiments should be conducted within such leachate plumes. The injection of known amounts of organic solutes and the subsequent determination of their distributions at later times has been shown to provide the required process rates under the realistic field conditions (Barker and Patrick, 1985). We feel that there is a high likelihood that the results could be applied to other leachate plumes as long as they are similar in their biogeochemical environment.

Additional monitoring of the North Bay, Woolwich and New Borden leachate plumes is also warranted. Specific questions about the groundwater geochemistry remain at each site, especially as to the spatial distribution of redox levels and microbial zonation. In addition, the migration of organics at North Bay and Woolwich is herein interpreted to be essentially stagnant or to have reached a quasi steady state. This should be tested by sampling of these plumes in 1987 and 1988. Additionally, some contaminants of interest were not followed in the current study. In particular, the distribution of other volatile organics such as acetone, tetrahydrofuran and 1,4-dioxane should be determined at these three sites in 1987 and 1988, so their mobility can be evaluated. Other researchers, including MOE scientists who are concerned about the mobility of certain other organics in leachate plumes should be encouraged to use the instrumented plumes studied in this project. As such, these sites represent valuable resources for the study of organic and inorganic contaminant transport in groundwater.

# 4

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# Appendix A

# WOOLICH LANDFILL SITE

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A - 1

# AQUIFER EVALUATION PROCEDURES - CORE ACQUISITION AND AN ASSESSMENT OF SLUG TESTS

by

Michael Marino Zapico

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presented to the University of Waterloo
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"...All things are connected. Whatever befalls the earth befalls the sons of [the] earth..."

excerpt from a letter by Chief Sealth, Duwamish Tribe, State of Washington to President Franklin Pierce in 1855.

# ABSTRACT

Aquifer studies in contaminant hydrogeological investigations commonly involve complimentary laboratory and field tests for the determination of hydraulic conductivity. The laboratory studies generally require representative samples of aquifer materials for permeameter tests or grain-size analyses for the Hazen method, while the field phase usually involves slug tests. This thesis pertains to both of these topics. Firstly, the design and evaluation of a new core barrel is described, followed by an application of the core barrel in a comparison of hydraulic conductivity results from slug tests to laboratory tests on the core samples.

The coring device was developed to obtain long and relatively undisturbed samples of saturated cohesionless sand and gravel. The coring device, which includes a wireline and piston, was developed specifically for use during hollow-stem auger drilling but it also offers possibilities for cable-tool and rotary-drilling. The core barrel consists of an inner liner made of inexpensive aluminum or plastic tubing, a piston for core recovery, and an exterior steel housing that protects the liner when the core barrel is driven into the aquifer. The core barrel, which is approximately 1.6 m (5.6 ft) long, is advanced ahead of the lead auger by hammering at the surface on drill rods that are attached to the core barrel. After the sampler has been driven 1.5 m (5 ft), the drill rods are detached and a wireline is used to hoist the core barrel, with the sample contained in the aluminum or plastic liner, to the surface. A vacuum developed by the piston during the coring operation provides good recovery of both the sediment and aquifer fluids contained in the sediment. In the field

the sample tubes can be easily split along their length for on-site inspection or they can be capped with the pore water fluids inside and transported to the the laboratory. The cores are 5 cm (2 in) in diameter by 1.5 m (5 ft) long. Core acquisition to depths of 35 m (115 ft), with an average recovery of 90%, has become a routine operation in University of Waterloo aquifer studies. A large diameter (12.7 cm (5 in)) version has also been used successfully. Nearly continuous sample sequences from sand and gravel aquifers have been obtained for studies of sedimentology, hydraulic conductivity, hydrogeochemistry, and microbiology.

The core barrel described above was instrumental in providing an opportunity to compare the laboratory hydraulic conductivity values derived from the core samples with the field hydraulic conductivities obtained from slug tests. The slug tests were performed in five wells screened over approximately 55% of a 20 m (66 ft) thick aquifer. The wells were installed using conventional hollow-stem augers in a glaciofluvial sand and gravel aquifer near a landfill in Southern Ontario. An average of 50 packer-slug tests on 20 cm (8 in) vertical intervals were conducted in each hole with a pressure tranducer and double-packer system. Aquifer core samples obtained from holes adjacent to each well were used to generate permeameter and Hazen hydraulic conductivity profiles from 950 and 200 core samples, respectively. Each sample was 5 cm (2 in) long. The permeameter and Hazen data show four orders of magnitude variability between minimum and maximum values in each of the five holes, whereas the variability in the packer-slug test values does not exceed 1.5 orders of magnitude. The profiles of the hydraulic conductivities derived from these methods demonstrate that values obtained from packer-slug tests in conventional PVC wells in augered holes fail to represent the vertical variability in hydraulic conductivity present in this aquifer; as a consequence there is a loss of resolution of high and low hydraulic conductivity zones. The study indicates that the slug tests are strongly influenced by the backfill and caved-in sediments in the disturbed zone in an auger drilled borehole.

# PREAMBLE

This thesis consists of two parts. Part 1 pertains to a core barrel developed for obtaining 1.5 m long relatively undisturbed samples of cohesionless sand and gravel from below the water table. Part 2 is an evaluation of hydraulic conductivities from packer-slug tests by means of comparison with values obtained from permeameter tests and from the Hazen method based on grain-size analyses. The laboratory-determined hydraulic conductivities were obtained from core samples acquired with the core barrel described in Part 1. Each part has been prepared as a completed document that can stand alone for publication purposes.

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## Part 1

# A WIRELINE PISTON CORE BARREL FOR SAMPLING COHESIONLESS SAND AND GRAVEL BELOW THE WATER TABLE

# I

# INTRODUCTION

The acquisition of relatively undisturbed core samples from below the water table in deposits of cohesionless sand or gravel is fraught with difficulties. Conventional coring techniques that involve Shelby tubes or split-spoon samplers of the geotechnical variety are generally not suitable because the lack of sample cohesion results in loss of the sand or gravel as the sampler is raised from the bottom of the borehole to the surface. In an attempt to overcome this problem, a variety of samplers have been developed, but each has particular deficiencies in versatility or efficiency.

This paper describes a new core-barrel sampler possessing enhanced capabilities for sample acquisition in saturated sand and gravel. The core barrel, referred to as the Waterloo cohesionless aquifer core barrel, was developed to provide a technique for acquiring, within a liner, relatively undisturbed samples of considerable length. In addition, the sampler minimizes the use of drill-rig time and also retains the original pore water within the sand or gravel contained inside the liner. Retention of the pore water is a feature that offers advantages in studies of groundwater chemistry or microbiology.

The core barrel can be used in conjunction with conventional hollow-stem augers, but it is expected that it will function equally well when used in conjunction with casings driven by cable-tool rigs or with rotary-drilled holes if the rotary rig is equipped with a pile/hammer drive system.

The sample is secured within an aluminum or plastic tube that can be easily removed from the core barrel when raised to the surface. The tube can either be split immediately using a jig-guided circular saw for on-site investigations or it can be capped and transported without disturbance to the laboratory. Pore-fluid sampling may be conducted on site by drilling holes through the liners and extracting samples with a syringe.

# II

# OVERVIEW OF CORE BARREL COMPONENTS AND THEIR FUNCTION

The core barrel consists of the following seven components: an exterior barrel, an interior sample tube, a hardened steel drive shoe, a piston, the wireline, a drill-rod reducer sub, and a drive head (Figure 1).

The core barrel is attached and lowered to the coring depth inside the hollow-stem augers or casings. The wireline is attached to the piston and passes inside the interior sample tube, through the drive head and along-side the drill rods inside the hollow-stem augers to a winch on the rig (Figure 2).

The drive-shoe cuts through the sand or gravel as the sampler is driven downward by pounding on the hammer-drive head attached to the end of the drill rod at the surface. The exterior barrel provides protection for the sample tube. As the sampler is driven into the undisturbed sediment, the wireline holds the piston at its initial position in the drive shoe at the elevation of the drill bit. During the coring operation, the entire length of the core barrel travels past the immobilized piston. At the end of the coring operation the piston is positioned at the top of the core barrel. A suction is developed on the pore water fluids and the sediment from the time the core barrel is driven past the piston. This suction is preserved until the piston is removed from the liner.

The suction is effective in retaining both the sediment and the pore fluids within the sampler and alleviates the need to use a catcher in the drive shoe. In addition to the suction developed by the piston, friction between the sand grains and the inner liner also assists in retaining the sample. The sampler works best when a drilling-mud slurry is used. The slurry is pumped down the augers where it reduces sediment inflow into the augers. Thus, the core barrel usually encounters a minimal amount of sediment inside the augers as it is lowered to the bottom of the borehole in preparation to core the undisturbed aquifer.

The wireline serves two purposes: it holds the piston stationary when the core barrel is driven downwards and hoists the sampler rapidly to the surface. This avoids sample loss caused by the delay and the vibrations that accompany drill-rod hoisting and disconnection.

# III

# DESIGN CONSIDERATIONS

In the sand aquifer at the Woolwich landfill described by Cherry (1983), coring was initially attempted with a variety of samplers. Each had specific limitations, such as poor sample recovery or short samples with frequent damage to the sampler. To compensate for these deficiencies, the sampler describe in this paper was designed to have efficient sample recovery, to obtain long samples (at least the length of a standard hollow-stem auger flight), and to be capable of coring gravel. Prior to the development of this core barrel, the piston sampler described by Munch and Killey (1985) was used and was found to be incapable of coring through previously undiscovered zones of pebbly sand or gravel in the Woolwich aquifer although it performed reasonably well in soft sand and silt. However, combining features from this device with some features included in other samplers led to the development of the Waterloo cohesionless aquifer core barrel.

To minimize sample loss while raising samples to the surface, the sampler must be separated from the drill-rods prior to recovery by the wireline in the manner described by Munch and Killey (1985). This required that the drive-head be fitted with a left-threaded pin to allow separation of the sampler from the drill-rods after the core barrel is driven into the aquifer. To provide this capability, a reducer sub from standard right-hand threads on the drill rods was threaded to the left-hand threads on the drive head in the manner described by Munch and Killey. To enable the piston and cable to travel freely in the barrel, a cable hole was installed in the drive head.

The aluminum liner and piston combination used by Munch and Killey had proven effective in the retention of fine sand, but ineffective when coarse or dense sediments were encountered. This required the development of an exterior housing and a drive shoe.

A seamless tube of mechanical-grade steel was used for construction of the exterior barrel to protect the inner sample tube. Both ends were threaded to allow reversal of the barrel in case one set of threads was damaged. To accommodate the inner sample tube and piston, the drive shoe was provided with an inner lip where the insert sits. This provided smooth passage for the piston and sediment, and prevented sediment from entering the annular space between the insert and the exterior barrel. The drive shoe was bevelled and hardened to provide a cutting edge.

The piston itself comprises an upper housing where the cable or wireline is attached and a lower portion where four rubber washers and brass spacers are attached. The rubber washers were periodically replaced when damaged. The locknut at the end of the washer spindle was adjusted to provide sufficient spreading of the washers but not overtightened to impede the travel of the piston. The washer configuration provided sufficient suction to retain pore fluids and prevent significant mixing. The initial position of the piston in the drive shoe also prevents entry of cuttings ("wash") into the core barrel. The piston develops enough suction to overcome the vacuum developed in the void where the sample has been obtained and gravity effects, which have been known to pull sediment out of other samplers when the device is lifted off the bottom of the borehole.

The inner barrel may be either aluminum or plastic tubing. The length of the inner barrel was designed to allow retraction of the piston into the uppermost portion to yield an effective recovery length of 1.5 m (5 ft).

Inexpensive aluminum tubing is normally used in the core barrel. It iss purchased from irrigation pipe supply outlets in 9 m (30 ft) sections an cut to fit the length of the core barrel. Industrial-grade thin-walled plastic tubing, commonly used in built-in vacuum cleaning systems, has also been used successfully. A sample interval of 1.5 m (5 ft) was chosen to correspond to 1.5 m (5 ft) auger flights so that the sampling and drilling operation could be synchronized and rapidly advanced.

The diameter of the core barrel was selected to correspond to the outside diameter of standard commercial tubing. The core barrel can, therefore, be constructed to any full size diameter. To explore the possibility of obtaining larger diameter aquifer samples, a 13 cm (5 in) diameter sampler was constructed and used successfully on a trial basis with an average recoverery of 85%. Minor modifications in design were necessary to scale up the piston to accomodate the heavier sampler. The larger sampler requires that larger 15 cm (6 in) inside diameter augers be used in lieu of standard 8.5 cm (3.25 in) augers.

# IV

# CORING OPERATION

The borehole is drilled down to the top of the coring depth using standard hollow-stem augers with an inside diameter of 8.25 cm (3 1/4 in.) or larger with a standard center bit/plug and drill rods. The drilling/coring operation is advanced in the conventional manner, except that a drilling mud is pumped down the augers. The drilling mud is not circulated as in rotary drilling, but rather the augers are filled with the drilling mud for a few auger flights above the watertable and allowed to seep out from around the drill bit to form a filter cake within the borehole. The density and viscosity of the mud is selected to suit conditions encountered. If sand flows into the augers, a mixture of bentonite and barite should be used. Whereas when silt or clay are present, natural mud mixes with the bentonite to achieve the desired result.

The initial weight of the bentonite mud should be approximately $9.6 \times 10^{-1}$ kg/L (8 lb/gal), roughly 1 1/2 minute mud, (determined in the field by using a Marsh funnel). Generally, it is increased to approximately 1.08 kg/L (9 lb/gal), or 2 minute mud. If the mud fails to prevent sand from entering the augers, then barite (Baroid) should be added to increase the mud weight to around 1.2 to 1.32 kg/L (10-11 lb/gal). The mud should be added soon after the water table has been encountered and no later than two flights of augers prior to coring in order to allow the mud to adequately create a filter cake and balance formation pressures.

Before coring, the center bit/plug must be removed. To break any suction and to allow the drilling mud to pass around the center bit requires that the center bit be rotated while pulling out of the augers. A worm groove along the center bit facilitates passage of the mud. The center bit should be rotated for 1 or 2 auger flights. Pulling out of the hole should proceed slowly to avoid any downhole suction causing the entry of fluidized sediments into the annulus of the augers. Once the center bit is retrieved and removed, the core barrel is connected to the drill rods by the left-threaded sub. Cable, equal to the coring depth, is then payed out so that there is no tension on the piston when running in the hole. This could otherwise cause the piston to rise prematurely from the drive shoe into the core barrel. The piston must remain flush with the drive shoe cutting edge until the coring depth is reached. This prevents cuttings from entering the core barrel. A five foot drill rod is attached to the last drill rod at the surface and marked with chalk at 30.5 cm (1 ft) intervals. This permits monitoring of the core barrel penetration. The hammer drive head and hammer are then positioned at the top of the drill rods. Slack on the cable is taken up so that it is slightly taut. Occasionally, the drill rods drop at this moment, which is an indication that the piston has entered the core barrel. During the coring operation, the piston remains stationary as the core barrel is advanced. The relative movement between the core barrel and the piston develops a suction on the cored sediments.

Both 308 and 748 kg (140 and 340 lb) hydraulic drive hammers have been used with CME Model 55 and 75 drill rigs in Ontario and Massachusetts. Use of the 748 kg (340 lb) hammer advances the coring operation so rapidly that in coarse to very coarse sands, the core barrel was fully advanced in 1-2 minutes, however, it appears that when the sampler is driven too rapidly into the aquifer that the sediment becomes sucked into the core barrel and excessively disturbed by the rapid passage of the sampler past the piston (D. Leblanc, personal communication, 1986).

After the core barrel has been driven 1.5 m, the hammer drive head and hammer are removed and a swivel head and cable are attached to the drill rods. The core barrel is then slowly lifted approximately 0.3-0.6 m (1-2 ft) while still attached to the drill rods in order to free the sampler from the cored interval. The sampler is then re-seated on the bottom once tension is released from the drill rods. A pipe wrench is then attached to the drill rods and rotated counterclockwise to break connection with the core barrel downhole. A slight hop is usually noticed when the connection is broken. Approximately 5-6 complete turns are required to disconnect the left threaded sub from the sampler. The wireline should be kept taut by pulling it away from the drill rods in order to avoid it being wrapped around the drill rods. The cable is grasped in order to monitor the core barrel when the drill rods are hoisted. If the cable slackens at this moment, it is necessary to lower the drill rods and core barrel under their own weight and to push the sampler just into the cored interval so that the drill rods can be disconnected from the core barrel. The core barrel should only be recovered via the drill rods if all the drill rods can be removed in one hoist, otherwise there is considerable risk of sample loss due to vibrations when the drill rods are disconnected.

The drill rods are then pulled out of the hole and laid down and the core barrel cable is reeled in to hoist the barrel to the surface. Reeling in the cable should not proceed too rapidly because sediment loss could occur when the vacuum developed by the piston is overcome by the vacuum developed when the core barrel is hauled too rapidly through the fluid filled augers. The drill rod and cable should be wiped down during recovery to remove drilling fluid.

The core barrel is then laid in a pipe vise and the drive shoe removed. Slack on the cable may be necessary to allow the core insert to be freely removed. The insert is then pulled out of the outer barrel and capped at the lower end. The upper portion is then cut with a pipe cutter just below the piston and similarly capped. It is generally easier to remove the piston prior to cutting the insert because there is more core barrel to grasp for leverage to work the piston free. The piston develops considerable suction and requires some effort to extract. The depth of the sample and orientation is then noted on the exterior of the barrel.

While the drill crew is running in the hole with the drill rods and the center bit/plug and augering down to the next coring depth, the core barrel can be wiped down and cleaned. A new insert is then loaded into the exterior housing and the piston reset. After the previously cored interval has been augered, and the center bit/plug retrieved, the "loaded" core barrel is run back in the borehole to resume the coring operation.

For sample description and usage, the core inserts are subsequently split longitudinally in a jig with a circular saw mounted with a carbide blade. The cores are split by cutting the insert tangentially, forming a 'V' shape cut. This provides a wider cut which just grazes the sample surface inside the liner.

Because the aluminum inserts are rolled and welded by the manufacturer there is a tendency for the barrel to snap apart when cut. To prevent this, small "bridges" are left at each end and in the middle of the insert to hold the barrel together.

These "bridges" are broken by inserting a screw driver into the cut and twisting once the core barrel is ready to be opened. Shards of aluminum or plastic are thrown by the saw and safety glasses are recommended. The saw and generator should be well grounded because of the formation fluids in the split cores.

# V

# CORE BARREL PERFORMANCE AT THREE SITES

The Waterloo cohesionless aquifer core barrel described here has been used in groundwater contamination studies in unconfined sand and gravel aquifers at two landfill sites: the Woolwich site in southern Ontario and the North Bay site in northern Ontario, both described by Cherry et al. (1983) and Reinhard et al. (1984). The sampler has also been used by the United States Geological Survey Water Resources Division in an investigation of a sand and gravel aquifer in Cape Cod, Massachusetts. The wide variety in the types of sand and gravel and the hydrologic conditions encountered at these three sites has provided a basis for assessing the versatility of the sampler.

The sampler was developed in a trial and error period during drilling operations at the Woolwich site where the thickness of the glaciofluvial sediments range from 16-43 m (52-141 ft) and the depth to the water table is between 1.7-21m (6-69 ft). A CME 75 drill rig equipped with hollow-stem augers and the bentonite mud technique was used to obtain approximately 49 m (160 ft) of core with an average recovery of 88%. Cores were recovered from a maximum depth of 22 m (72 ft) below the watertable. The maximum depth cored was 34 m (112 ft). Aquifer materials ranged in texture from very fine sand to medium gravel. The contact at the base of the aquifer, which consists of a dense pebbly clay till, was also successfully cored.

Although the close to 90% recovery is good, consideration of the causes of the 10% loss may lead to even better recovery. Potential causes are as follows:

1. piston washers not adequately expanded so that a strong suction was not developed during coring.
2. excessively rapid wireline recovery resulting in a stronger suction at the open drive shoe of the sampler than that generated by the piston.
3. excessive rate of advancement of the core barrel into the formation, which may cause a decrease in the density of the sediment with spreading in the core barrel (an occurance with the 748 kg (340 lb) hammer).
4. presence of cobbles larger than the inside diameter of the drive shoe

Also some of the apparent sample loss may actually be sample compaction. The effects of the first three potential causes can be minimized if care is taken during core barrel preparation and operation.

Gravel interbeds encountered during the coring operation did not impede advancement of the sampler. Recovery of interbedded gravel and sand was as good as for massive sand. In some cases, cobble-size material close to the inside diameter of the drive shoe and sample liners was recovered.

At the North Bay site, cores were taken from the water table, at just a metre below the surface, to the base of the aquifer 18 m (59 ft) below ground surface. The texture of the aquifer varies from fine silty sand to a very coarse clean sand. The results of the aquifer investigation are described by Moore (1986).

Twenty-nine cores were taken with the sampler. However, three techniques were employed by the operators to evaluate the possibility for increasing the speed of the coring operation. The average recovery varied with the method used. Initially, fifteen cores were taken without use of the piston and cable. Retrieval of the sampler was performed with the drill rods. This method yielded an average core recovery of

66%. The highest recovery was achieved when the sampler was used as designed. Twelve cores taken when the cable and piston were used yielded an average recovery of 86%. Two cores taken with the piston but without the cable provided a core recovery of 62%. The lower core recovery probably occurred because the sediment became compacted against the piston in the core barrel, causing sediment ahead of the sampler to be compacted or excluded. Under these circumstances the only force causing the piston to "travel upwards" would be that excerted by sediment entering the core barrel.

At a site of sewage contamination in Cape Cod, described by Leblanc (1984), the Waterloo cohesionless aquifer core barrel was used with a CME 55 drill rig at two locations to obtain a total of 18 cores. The cores were taken from a clean, medium to very coarse sand. Gravel interbeds with pebbles 2-3 cm in diameter were also sampled. The silt and clay content was less than 1%. Cores were taken continuously to a maximum depth of 20 m (65 ft) with 97% recovery. Because the recovery was uniform and a void space was noted above the sediment but below the piston, it was concluded that the sediment was compacted approximately 3%.

It may be necessary to avoid the use of drilling mud in some field studies such as those that require microbiological or geochemical samples. In these studies the bentonite may contaminate the samples. To avoid the use of drilling mud, a special drill bit with a cone shaped door was used with 8.25 cm (3.25 in) inside diameter augers. This drill bit was developed by R.W. Gillham at the University of Waterloo. Drilling was conducted in the usual manner except that no center bit was used. Once the designated coring depth was encountered, the core barrel was lowered down the augers. To establish hydrostatic equilibrium between the borehole and the inside of the augers, water was pumped into the augers. This reduced the inflow of saturated sediments into the augers once the "doors" were forced open.

The core barrel was then pushed through the "doors" and advanced as previously decribed. Recovery of the core barrel was conducted in the usual manner except that water was pumped down the augers using a 0.95 cm (0.375 in.) polyethylene tube to free the core barrel from any sediment that entered the augers.

The augers were retrieved from the borehole and the "doors" re-set. The auger flights where subsequently lowered downhole and drilling resumed to the next "target" core depth. Because all of the augers have to be pulled to the surface in order to re-set the "doors", coring in this manner is relatively slow.

## VI

## ELECTRICAL CONDUCTANCE AND HYDRAULIC CONDUCTIVITY PROFILING

Because both pore water and sediment samples can be obtained with this core barrel, profiles of groundwater chemistry and hydraulic conductivity can be generated. At the Cape Cod site, the cores were used for on-site measurement of electrical conductance while samples obtained from the Woolwich and North Bay landfill sites have been used for detailed hydraulic conductivity profiles.

### 6.1 Pore Water Sampling

Groundwater from eight cores retrieved from within the sewage plume at the Cape Cod site were measured for electrical conductance. The values were found to correspond to values obtained from adjacent multilevel samplers, (Figure 3). The maximum value measured was 375 $\mu$ S relative to a background of 35 $\mu$ S. To obtain these samples, the full liner and piston were removed from the exterior housing. The liner was inclined to allow pore water to drain into a sample vial placed below the liner. Drainage was initiated when the vacuum was broken by cutting through the liner with a hacksaw.

In a more recent trial at this site, cores were taken across the interface between shallow recharge water and the deeper contaminant plume. The electrical conductance was measured along the length of the core liner by puncturing the liner with a drill and extracting pore water fluids with a syringe. A sharp increase was observed across the top of the plume. These values corresponded closely to values from adjacent multilevel samplers, (D. Leblanc, personal communication, 1986).

Other methods that can be employed to extract pore fluids from core samples have been addressed in the literature. Two of these, centrifugation and squeezing, are described by Munch and Killey (1985) and Patterson et al (1985), respectively.

## 6.2 Hydraulic Conductivity Profiling

Detailed hydraulic conductivity profiling provides a means to ascertain the vertical variability in the flow field of an aquifer. From these data, average linear groundwater velocity profiles and the arithmetic, geometric, and harmonic means can be calculated to characterize the advective flow field.

For the hydraulic conductivity tests, sand extracted from the split core barrel in 5 cm segments was mixed and a 50 gram sub-sample of this mixture was placed in a permeameter. The cross sectional area of the permeameter is 11.30 $cm^2$ (1.75 $in^2$) with the samples ranging from 2.5 to 3.0 cm (0.98 to 1.2 in) in length. The hydraulic conductivity was measured under either falling head or constant head conditions. Hydraulic conductivity profiles of this type (Figure 4) was generated for cores recovered from the Woolwich and North Bay sites to permit hydrostratigraphic correlations and aquifer characterization. The profiles shown in Figure 4 indicate a considerable degree of heterogeneity in the Woolwich aquifer. Without continuous cores, the degree of heterogeneity would not have been seen. Studies by Mackay et al (1987) and Sudicky (1987) have found velocities based on the geometric means of hydraulic conductivity obtained from permeameter tests on core subsamples of this size to compare favorably with field tracer tests. In addition, Moore (1986) used mean values of hydraulic conductivity obtained from permeameter profiles from numerous samples obtained with the core barrel to determine values of mean lateral ground water velocity in a large contaminant plume.

Vertical hydraulic conductivities may also be determined by cutting the core transversely and then mounting the core segment, contained in the original liner, in a permeameter as described by Munch and Killey (1985). Alternatively, the entire core may be used as a permeameter by installing manometers to determine the head loss at specific intervals along its length to generate hydraulic conductivity profiles. The advantage of this technique is that sedimentological structures are preserved.

# VII

# SUMMMARY OF CONCLUSIONS

The core barrel described in this paper here provides a remedy for the problem of obtaining long, relatively undisturbed samples from below the water table in cohesionless sand and gravel. When used in conjunction with a drilling mud composed of either bentonite or bentonite/barite, core recovery of 80-97% can be accomplished routinely and quickly.

Because both pore water and sediment samples can be obtained with this core barrel, profiles of groundwater chemistry and hydraulic conductivity can be generated. The latter can be used for detailed groundwater velocity profiling and the determination of the arithmetic, geometric, and harmonic means to characterize the aquifer and the ground water flow regime. A large-diameter version of the core barrel provides an opportunity to obtain large aquifer samples from which smaller samples can be aseptically cut from the core for microbiological or geochemical studies when the avoidance of sample contamination is desired.

## VIII

## ACKNOWLEDGEMENTS

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Michael Moore and Nancy Gensky of the University of Waterloo were principal members of the field crew during the trials of the sampler at the North Bay site. The trials at the Cape Cod site were undertaken by Dennis LeBlanc and colleagues of the U.S. Geological Survey, Water Resources Division in cooperation with myself. I extend my thanks to the participants in these field trials for the helpful comments and data that they have provided.

I would like to thank J.A. Cherry for his comments in reviewing this paper and Sam Vales, driller, for his technical expertise that provided the link between concept and reality.

Machining services were provided by personnel in the Science Machine Shop of the University of Waterloo, specifically Chris Gendron, Ernst Elissat, and Reginald Graf.

# IX

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# X

## LIST OF FIGURES

Figure 1. Waterloo Aquifer Piston Core Barrel-Schematic

Figure 2. Coring Operation

Figure 3. Specific Conductance versus Depth Profile, Cape Cod, Massachusetts

Figure 4. Hydraulic Conductivity versus Depth Profiles, Woolwich Landfill, Waterloo, Ontario.

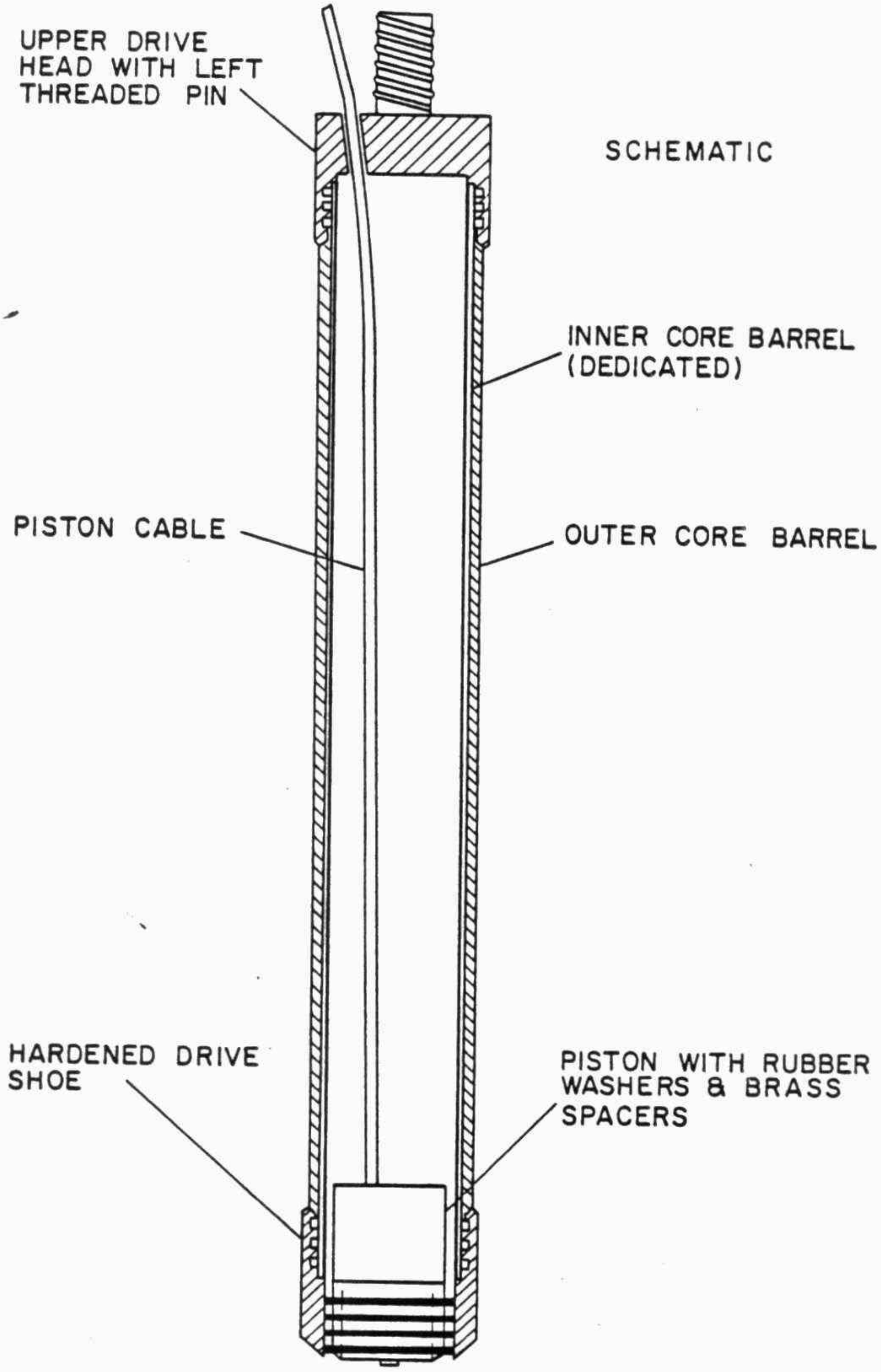
UPPER DRIVE HEAD WITH LEFT THREADED PIN
SCHEMATIC
INNER CORE BARREL (DEDICATED)
PISTON CABLE
OUTER CORE BARREL
HARDENED DRIVE SHOE
PISTON WITH RUBBER WASHERS & BRASS SPACERS

FIGURE 1. WATERLOO COHESIONLESS AQUIFER CORE BARREL

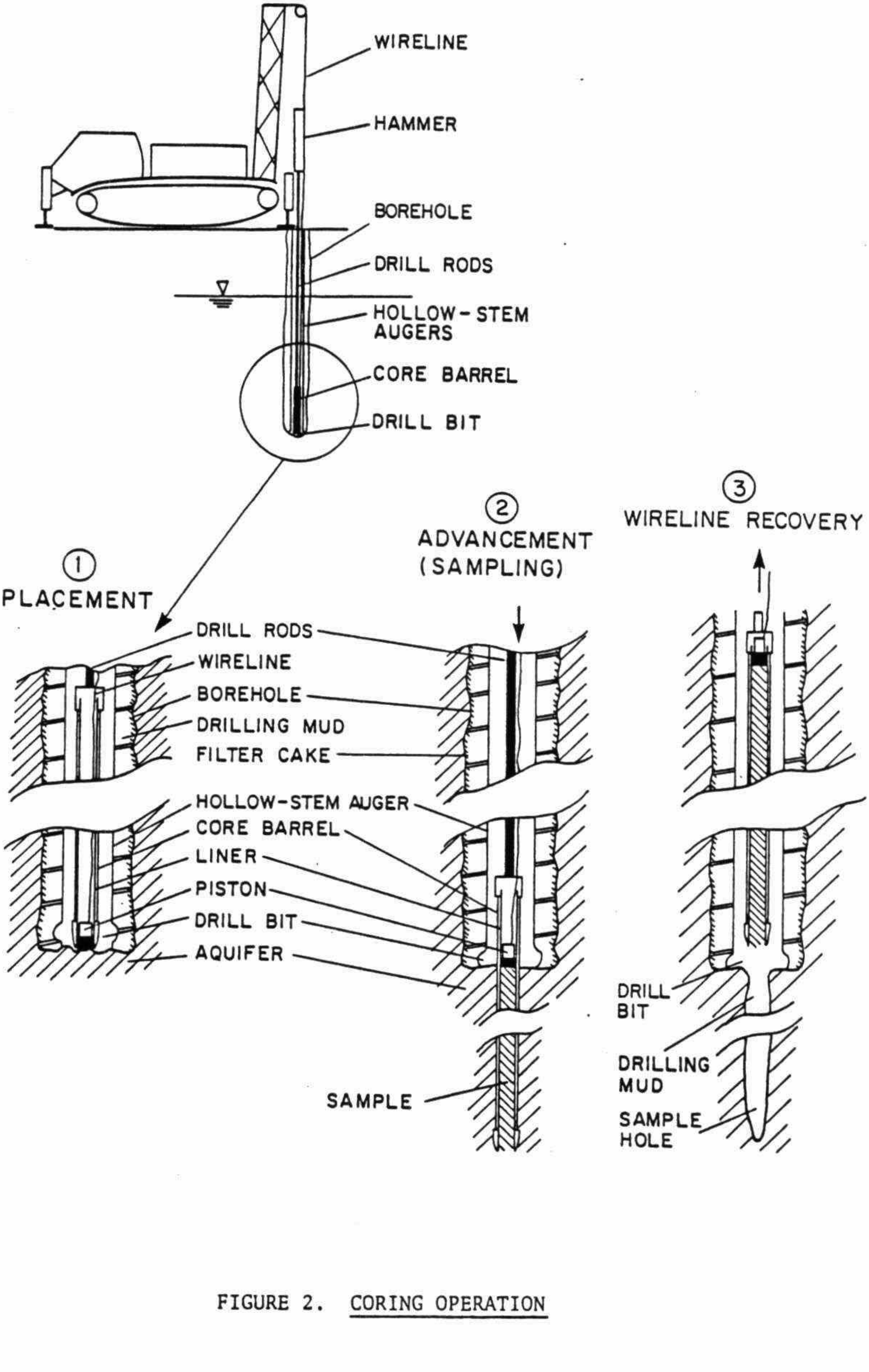

FIGURE 2. CORING OPERATION

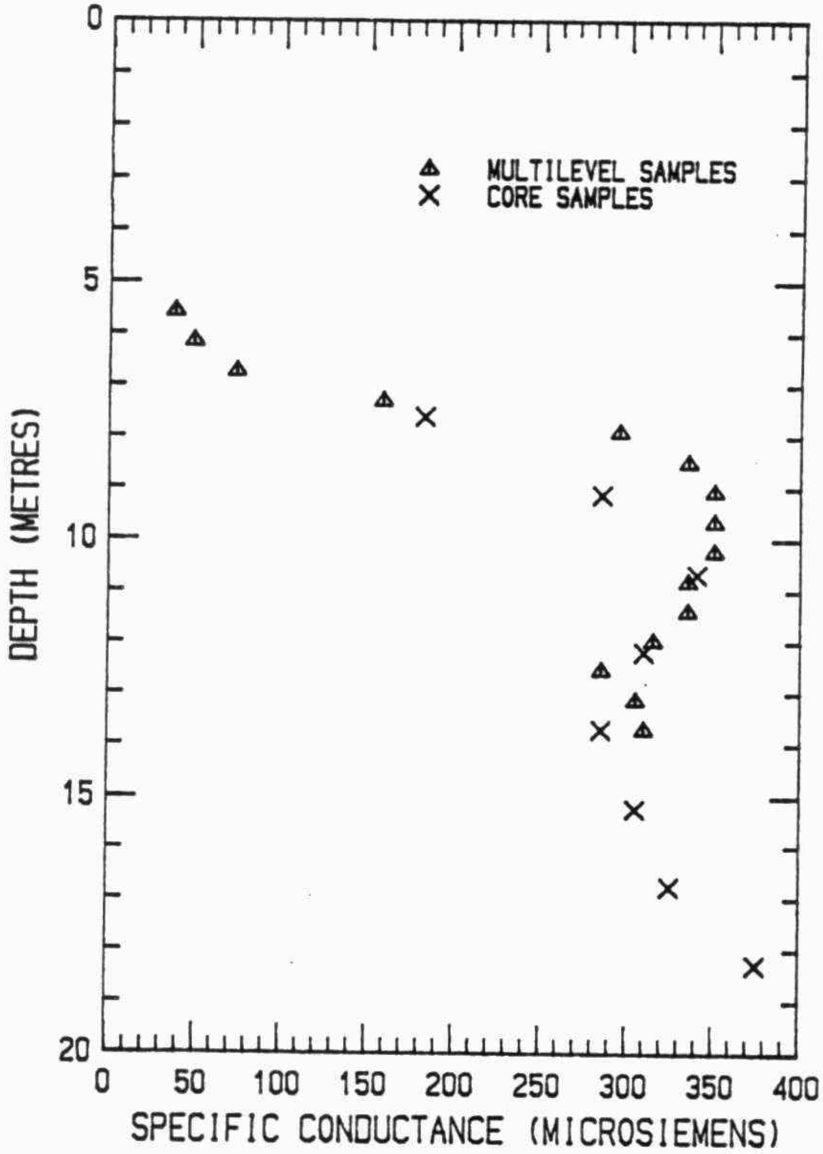

FIGURE 3. SPECIFIC CONDUCTANCE VERSUS DEPTH PROFILE

Multilevel sampler data compared with pore-water samples extracted from core samples, corrected to 25°C. From the U.S. Geological Survey Cape Cod Research Site, Toxic-Waste Ground-Water Contamination Program. (Personal Communication with D. LeBlanc, U.S.G.S., 1985).

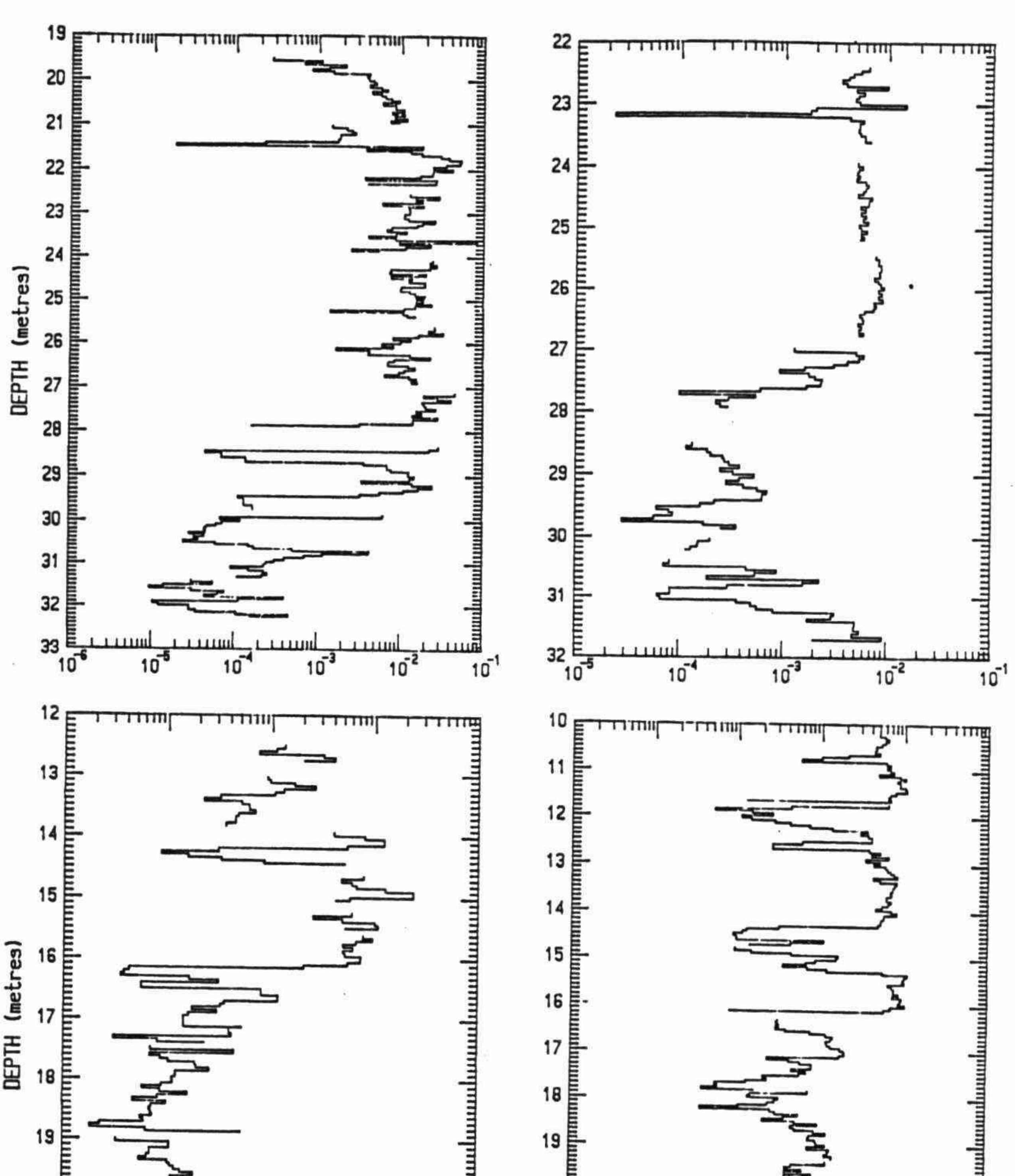

FIGURE 4. HYDRAULIC CONDUCTIVITY VERSUS DEPTH PROFILE, WOOLWICH LANDFILL, WATERLOO, ONTARIO. Core hole sites, clockwise from upper left; C-1, C-3, C-4, and C-5.

## Part 2

# AN ASSESSMENT OF SLUG TESTS IN AUGERED WELLS IN A SAND AQUIFER

# XI

# INTRODUCTION

A slug test is a widely used method in the determination of hydraulic conductivity in piezometers or wells because it can be conducted quickly and inexpensively. In this study the term slug test is used in the general sense and thus represents either a slug or bail test. In a slug test the equilibrium waterlevel in a piezometer or well is quickly changed and the level is then monitored with respect to time as it returns to the initial level. The hydraulic conductivity is directly proportional to the rate of inflow.

In the shallow cohesionless, sand and gravel aquifers that are commonly found in the glaciated regions of North America, piezometers or monitoring wells are commonly installed by hollow-stem auger drilling. The augers create a borehole generally two or three times the outside diameter of the piezometer or well. Once the borehole is drilled, the well is lowered inside the augers to the bottom of the borehole. The augers are removed and the borehole is allowed to cave-in around the screen. The cave-in below the water table forms a natural, albeit poorly differentiated, sand and gravel pack. If the borehole does not cave-in completely, the open portion of the hole is normally backfilled with sediment brought to the surface during the drilling. The caved-in and backfilled sediment is referred to here as the disturbed zone. This disturbed zone around the well screen is commonly assumed to behave hydraulically as if it is identical to the undisturbed aquifer. However, in comparison to the aquifer the slug test results tests may actually reflect greater or lesser head loss in the caved-in or backfilled material adjacent to the well screen. Consequently disturbance in the aquifer material around the well screen due to augering may lead to calculated hydraulic conductivity values that do not represent the aquifer.

A commonly-used method for analysing slug test data was presented in a treatise by Hvorslev (1951) who provides not only a theory for analysis based on Darcy's law but also describes possible errors and geometric considerations associated with slug tests. Hvorslev stated in the conclusion of his treatise "...it is advisable to exert great caution in the practical application of the results obtained by this method.".

The purpose of this study is to ascertain the effect of hollow-stem augering in a cohesionless sand and gravel aquifer on the determination of hydraulic conductivity by slug tests in wells in augered holes. This is accomplished by comparing the hydraulic conductivities from slug tests performed using a double-packer system with those obtained from laboratory tests on core samples.

Two types of laboratory procedures were used: permeameter tests of aquifer samples obtained using the Waterloo cohesionless aquifer core barrel and the Hazen method based on grain-size analyses of these core samples. Nearly 1000 permeameter tests were conducted on 5 cm long subsamples from 1.5 m long cores to provide detailed resolution of the vertical variability in hydraulic conductivity in the five boreholes. The Hazen method was performed on approximately 20% of these samples to obtain an independent confirmation of the validity of the permeameter test results.

The cores were acquired using the core barrel described in Part 1, at five sites located along the approximate centerline of the contaminant plume emmanating from the Woolwich landfill near Waterloo, Ontario. The aquifer and plume are described by Cherry (1983). The Woolwich aquifer was selected because the aquifer materials range from coarse sand and gravel to silty clay and therfore represent a broad range of sediment typical of glaciofluvial aquifers. The packer-slug tests were conducted in 5 cm (2 in) diameter wells adjacent to each of the five cored sites. Approximately 300-20 cm (8 in) tests were performed in wells with long screens.

## XII

## FIELD AND LABORATORY METHODS

The study was conducted in two phases; a field phase and a laboratory phase. The field phase involved the installation of five - 5 cm (2 inch) diameter PVC wells with screens ranging in length between 7.5 and 13 m (24.6 and 42.6 ft). The spacing between the wells is approximately 260 m (850 ft) along the principal flow path of the leachate plume. The aquifer is screened over approximately 55% of its 20 m (66 ft) thickness. The depth to the water table ranges from 2.2 m (7 ft) to 16.5 m (54 ft). Cores were taken with the Waterloo cohesionless aquifer core barrel (described in Part 1) over the same intervals that were screened. The core holes were located between 1.5 - 2 m (5-6 ft) from the wells. The schematic cross section in figure 1 shows the locations of each of the paired wells and cored boreholes from the southeast corner of the landfill to the eastern limit of the study site along the approximate centerline of the leachate plume.

Samples extracted from the split cores were used in the laboratory tests. The laboratory phase required the extraction of sub-samples from each split core to subject them to permeameter tests and grain-size analyses for the Hazen method. Approximately 950 samples were removed from the cores and oven-dried before being packed in the permeameters. The hydraulic conductivity for each of these samples was determined by the falling-head permeameter method. A total of 203 samples were then choosen from the total sample population of 953 for the grain-size analyses.

## 12.1 Well Installation

The wells were installed using 18 cm (7 inch) outside blade diameter hollow-stem augers. The wells are constructed of Timco flush threaded, schedule 40 PVC pipe and screen. The screens have 0.02 mm (0.010 in) wide slots every 0.5 cm (1.3 in).

Rather than using a center-bit during the drilling operation, a reinforced rubber stopper was used in the cut-head during the installation of the well. To facilitate pushing the rubber stopper out of the cut-head, the augers were filled to approximately 50-60% of their length with water. Prior to pushing the rubber stopper out of the cut-head, the augers were lifted approximately 0.3 m (1 ft) off the bottom of the borehole and the well was then used to push-out the stopper. Water was the only drilling fluid used in the drilling operation.

Once the augers were removed from the ground, the hole was backfilled using only the borehole sediment brought to the surface during drilling. Occasionally the hole would partly cave-in or develope bridges, but this did not significantly interfer with backfilling the hole. Whether or not the hole completely caved-in below the watertable is difficult to definitatively ascertain, however because the amount of sediment remaining around the borehole after backfilling was generally small at all five sites, it was concluded that little caving occurred.

## 12.2 Packer-Slug Tests

A total of 300 slug tests using a double-packer system were performed, with approximately 50 of these tests being repeat tests. An average of 50 tests were conducted in each well.

The packer-slug testing system is comprised of a packer assembly and riser pipes, a pressure transducer and chart recorder, and a slug and tripod (Figure 2). The system was set up and operated by one person. Additional information on the design, construction, and operation of the system is presented in Appendix C. Prior to performing the tests, each well was developed by surging. The tests were performed in a sequence starting at the bottom and ending at the top of the screened interval.

The packer assembly consists of two packers, 24 cm (9.5 in) long, that are inflated by nitrogen. The testing interval, which is the distance between the packers, was adjustable and could be set to a minimum of 10 cm. A 20 cm interval was used in the study. The selection of the testing interval was based on bed thicknesses observed in the cores and also on logistical considerations. The spacing between the packers is achieved using threaded brass rods of various lengths. Riser pipes were used to connect the packer assembly with the surface. The pipes, 3.2 cm (1.25 in) outside diameter, were flush threaded. Two different lengths of pipe, 0.9 m (3 ft) and 3.0 m (10 ft), were used. The 0.9 m ( 3 ft) in length sections were used specifically near the top of the riser pipes so that the shorter pipe could be easily removed without disturbing the surface equipment as tests were performed at shallower and shallower depths. The packer inflation line was 0.32 cm (0.125 in) polypropylene "spagetti" tubing that was threaded through the inside of each riser pipe.

The pressure transducer was a Druck PDCR 10/D with 100 mV maximum output. The submerged operation depth was approximately 7 m (23 ft) including water displacement in the riser pipe. The sensitivity of the transducer was 0.5 cm, approximately 0.07 mV or 95 to 97% of the total slug rise. The transducer was connected to a chart recorder via an offset and attenutor box. Input signals were monitored by a digital voltmeter that was connected in line. The offset and attenuator box enabled the input signal to be calibrated with the chart recorder for 1 m (3 ft) head displacement and alleviated the need to convert between the input signal and the chart recorder values. The transducer recorder system was calibrated in the laboratory over 10 cm (4 in) changes in head.

Since the input signal was calibrated to be read directly in centimeters from the chart recorder, no conversion of the data was necessary when data points were read from the response curves as an example, Figure 3, shows the decrease in head with respect to time from one of the aquifer response curves. The time and change in head h(t) data was picked off the curves using templates for different chart recorder speeds.

### 12.3 Core Acquisition

The core barrel used to acquire the samples was developed as part of this overall project after other commercially available samplers failed to obtain the necessary samples. It is capable of acquiring 1.5 m (5 ft) long by 5 cm (2 in) relatively undisturbed cores of saturated sand and gravel. The interbedded nature of the aquifer is represented by beds of sand and gravel with occasional silt and clay. Cobbles up to 4-5 cm (1.5-2 in) were found in some gravel zones. Each core was housed in a dedicated aluminum liner. The core were obtained in front of the lead auger while the hole is advanced with hollow stem augers. A total of thirty-five 1.5 m long cores, approximately 8 per hole, were obtained with the core barrel with an average recovery of 90%. Each core was split longitudinally and samples were extracted every 5 cm for permeameter and grain-size analyses.

### 12.4 Permeameter Tests

The hydraulic conductivities of 953 samples were determined using five falling head permeameters. The samples, each 5 cm (2 in) long, were extracted from the split cores. The permeameters were made of plexiglass and were specifically designed to be compatable with the extracted sediment. They include a screened piston to preserve sample volume and compactness during the tests (figure 4). The permeameters were connected to one of three standpipes of different diameters. The permeameters and techniques used in these analyses are the same as those used by Sudicky (1987). The diameter of the standpipe used depended on the texture of the sediment, ie., coarse textured/high flow sediments required a large diameter (1.58 cm (0.62 inch)) standpipe, whereas fine grained sediments with a low flow rate were tested with a standpipe of 0.635 cm (0.25 inch). The screened piston was held in place by a threaded rod. Pressure on the sediment was maintained to prevent channelling and sediment displacement and preserve sample volume. The test length in the permeameter was variable and ranged between 2.5 to 3.0 cm (0.98 to 1.2 in) with a cross sectional area of 11.30 $cm^2$ (1.75 $in^2$). The screens in the intake and piston could be changed to a different mesh depending on the texture of the sediment.

When the 5 cm long samples were removed from the cores they were oven-dried at 90°C for 12 hours. Afterwards, any aggregates which formed in the oven were broken up by mortar and pestile and any particles greater than 2 mm (-1.0 phi) were removed from the total sample. The sample was mixed and a 50 g portion was put in the permeameter.

The piston was positioned at the top of the sample and entrapped air was displaced by low pressure flow (7 psi) of $CO_2$ for approximately 15 - 30 seconds. The sample was then saturated with de-aired water. The piston was firmly re-positioned on top of the sample by screwing the threaded rod holding the piston in place to ensure that the sample was not displaced either by de-airing or saturation and to preserve packing.

Air bubbles within the flow system were kept to a minimum by means of a closed flow system. For example, the discharge tube emptied into a water filled trough and the tube itself was kept filled with water by using a valve below the base of the permeameter. In addition, a peristaltic pump was used to pump the de-aired water into the permeameters and standpipes.

The permeameter tests were conducted under falling head conditions with an initial head of 2.3 m (7.5 ft) and the final head at approximately 1.0 m (3.28 ft) above the datum. The datum was established at the static water level in the catchment trough. The elapse time from the initial head to the final head was recorded along with the length of the sample. These variables were entered into the falling head equation (Todd 1980, page 74). Hydraulic conductivities were temperature corrected to the field values, which ranged from 6 to 10°C, according to the equation 1, obtained from (Cedergreen, 1977);

$$K_{field} = K_{lab}\left(\frac{\mu_{lab}}{\mu_{field}}\right) \tag{1}$$

where

$\mu_{lab}$ = viscosity of the laboratory water

$\mu_{field}$ = viscosity of the groundwater at the study site

$K_{lab}$ = lab hydraulic conductivity

$K_{field}$ = field hydraulic conductivity

This required daily monitoring of the laboratory water and a temperature survey for each location in the study site. The viscosity was then determined for the laboratory and groundwater according to equations 2 and 3, Chemical Rubber Company (CRC), (1983-84);

0-20°C

$$\log_{10}\mu_T = \frac{1301}{998.333 + 8.1855(T\text{-}20) + 0.00585(T\text{-}20)^2} - 1.30233 \tag{2}$$

20-100°C

$$\log_{10}\frac{\mu_T}{\mu_{20}} = \frac{1.3272\ (20\text{-}T) - 0.001053\ (T\text{-}20)^2}{T + 105} \tag{3}$$

where

$\mu_{20} = 1.002$ cp.

In the earliest stage of the permeameter tests an attempt was made to re-create field density and packing. This was achieved by vibrating several test samples in the permeameter using a modified engraving tool that had the cutting tip replaced with a rubber tip. The "engraver" or vibrator was connected to a timer to ensure consistency from sample to sample. Although a change in the sample length of 1 to 2 mm was noted, the change in the hydraulic conductivity ranged from nearly identical to a factor of 1.5 between vibrated and non-vibrated samples. Because the change was not significant this additional step was discontinued. Changes of less than one third of an order of magnitude were also noted in vibrator compaction tests conducted on permeameter samples by Moore (1986).

## 12.5 Grain-Size Analyses and Hazen Method

A total of 203 of the 953 core sub-samples were chosen for grain-size analyses. The selection of these samples was based on the hydraulic conductivity profiles from the permeameter tests which were generated for each 1.5 m core. Each core provided several sub-samples that were selected for parts of the core with extreme high and low hydraulic conductivity values. In addition, a sample was selected from the top and bottom of each core so that continuity between each core could be verified.

The samples were analysed by the hydrometer and sieve methods. Twenty-four hour hydrometer tests were performed first. Afterwards the samples were washed, oven-dried, and sieved at 1/2 phi intervals. All results were corrected to cummulative weight percent passing and plotted. To determine the hydraulic conductivity from the grain-size plots the Hazen method was used. The method, developed by A. Hazen in 1911, is described by Freeze and Cherry (1979) and Lyon (1985) and is most applicable to relatively clean, cohesionless sands and gravel where the hydraulic conductivity is greater than or equal to $10^{-3}$ cm/s. The resultant hydraulic conductivity (equation 4)

$$K = Ad_{10}^2 \tag{4}$$

is equal to the square of the effective grain-size diameter in millimeters for the 10% cummulative weight percent passing. The variable A is equal to 1.0 when $d_{10}$ (the effective grain-size diameter) is in millimeters.

# XIII

# RESULTS AND DISCUSSION

## 13.1 Permeameter Tests

Vertical profiles of the hydraulic conductivity data are presented in figures 5 and 6 for sites C-1 and C-5. These sites were selected for presentation because they exhibit the widest range in of textural variations. At all sites the hydraulic conductivities derived from the permeameter tests demonstrate four orders of magnitude variability from a low on the order of $10^{-5}$ cm/s to a high on the order of $10^{-2}$ cm/s. The individual hydraulic conductivity values for the permeameter, Hazen, and packer-slug tests are presented in Appendix A. Grain-size curves for each core are presented in Appendix B.

Although a correlation of hydrostratigraphic zones is beyond the scope of this study, it can be seen from these figures that specific zones can be identified. For example, figure 5 shows a major hydrostratigraphic interval from 21.5 to 28.4 m. This zone consists of moderately well sorted, medium to coarse sand and is dominated by hydraulic conductivities on the order of $10^{-2}$ cm/s. An interval such as this constitutes a major "high" K zone relative to overlying and underlying units. Similarly, figure 6 shows that the site is dominated by both a relatively "high" K zone in the $10^{-3}$ cm/s range from 14 to 16.2 m, underlain by a "low" K zone in the $10^{-5}$ to $10^{-4}$ cm/s range from 17.2 to 20.5 m. The "high" K zone consists of moderately sorted, interbedded silty sand and medium to coarse sand with some gravel. The "low" K zone ranges from moderately to poorly sorted and consists of interbedded silt and fine to medium sand with occasional gravel.

To compare permeameter values with the values derived from the Hazen method and slug tests, the arithmetic, geometric, and harmonic means have been computed. These values are presented in Appendix A. Hydrogeologically, the means represent the bulk hydraulic conductivity for the aquifer. The arithmetic mean ($K_A$) represents the hydraulic conductivity along the bedding planes while the harmonic mean ($K_H$) represents the hydraulic conductivity orthogonal to the bedding. These means may be viewed in terms of the hydraulic conductivity elipsoid where the arithmetic mean is equivalent to an average hydraulic conductivity in the direction of the bedding and the harmonic mean is equivalent to an average hydraulic conductivity perpendicular to the bedding. The intermediate value is the geometric mean ($K_G$) that represents the hydraulic conductivity at some angle to the bedding. Because flow is seldom retricted to either along or orthogonal to the bedding the geometric mean tends to best represent the flow field where $K_A > K_G > K_H$.

The means for the permeameter tests are presented in Table 1 and shows the variability computed for each profile. Because the cored intervals did not overlap exactly on depth with the slug test intervals, only those 5 cm intervals that constituted a 20 cm test zone were included. Therefore, the 20 cm averaged intervals represent only those 5 cm intervals within a core that have been correlated on depth with the 20 cm packer-slug test intervals. The four correlated 5 cm samples per test interval were then averaged and are taken to be representative of the hydraulic conductivity across that test interval. In subsequent profiles and comparisons, these correlated and averaged 20 cm test zones are referred to as 20 cm averages.

## 13.2 Comparison of Hazen and Permeameter Results

Hydraulic conductivities derived from these two techniques are comparatively plotted in figure 7. The correlation coefficient computed for these values is 0.8212. The plot comprises 203 samples for which the two types of hydraulic conductivity values were obtained. Both methods yield four orders of magnitude variability in the hydraulic conductivity. Except for occasional random values the agreement between these two methods is quite close.

Tables 2a and b show the means computed for the Hazen method and the permeameter tests for the same samples, respectively. An examination of these values shows that the best agreement is observed with the geometric mean. The results are consistent for both C-1 and C-5 where the Hazen value is on the average 1.6 times greater than the permeameter value. The arithmetic and harmonic means do not however exhibit consistency between the two sites. At C-1 the arithmetic mean of Hazen values is 4 times larger than the permeameter value whereas at C-5 good agreement is observed between the two values and the permeameter values is approximately a factor of 1.2 greater than the Hazen value. The relationship between the harmonic mean values is reversed. At C-1 the permeameter value is approximately a factor of 2 greater than the Hazen value and at C-5 poor agreement is observed where the Hazen values is 4 times larger than the permeameter value. The inconsistent behaviour in $K_A$ and $K_H$ with respect to the range in the means may inadvertently be an artifact of the selection of samples used in the grain-size analyses.

## 13.3 Determination of the Hydraulic Conductivity and Installation Factor

It is usually assumed that the slug test determines the hydraulic conductivity of the undisturbed formation constituting the aquifer. However, there are three components in the test interval that influence flow across the zone of interest, these are; (a) the well screen, (b) the disturbed zone consisting of backfilled and caved-in sediment, and (c) the undisturbed formation. Each of these components has an influence on the flow between the piezometer or well and the aquifer such that the resultant hydraulic conductivity reflects the limiting resistance to flow. It is assumed that the well screen has been properly selected and provides negligible flow resistance. However, flow resistance in either the disturbed zone or the formation is measurable and the slug test is therefore a measure of the hydraulic conductivity in these latter two zones.

This geometric relationship between the well screen and the aquifer is commonly referred to as the shape factor (F) by Hvorslev and it is discussed more fully below. The shape factor is incorporated into an analysis known as Hvorslev's time lag method which is a linear regression analysis that determines the hydraulic conductivity ($H_o$), the elapse time (t), and the change in head (h) data from the response curves. The assumptions in the time lag method are; "(1) Darcy's Law is valid, (2) soil and water are incompressible, (3) artesian conditions prevail or that the flow required for pressure equalization does not cause any preceptible draw-down of the ground-water level", Hvorslev (1951). Storativity in the aquifer is also neglected. To facilitate the analysis of the packer-slug test results, a linear regression program was developed to compute the hydraulic conductivity. The program also required that the geometry of the installation (well) and borehole be defined, this was achieved by considering different "installation factors" (F/A). The installation factor is a new term that combines Hvorslev's shape factor (F), presented here as equation 7, with the cross sectional area (A) of the riser pipe or casing and is entered into the program at the beginning of the analysis. The shape factor introduced by Hvorslev considers the geometry of the test zone as a function of the length (L) and the diameter (D) of the test interval. In the packer-slug tests L, was a constant and set at 20 cm, however, D depends on how the diameter of the test zone is defined. To consider the different possible cases three installation factors were considered.

The first case assumed a partially-clogged well screen and thus accounts for impeded flow from the installation into the disturbed zone. In this case it was assumed that the disturbed zone had the same hydraulic conductivity as the aquifer.

The second case assumed that the well screen was not clogged but that the disturbed zone was poorly developed and thus had a lower bulk hydraulic conductivity than the formation.

The third case assumed both the well screen and the disturbed zoned provided negligible flow resistance. This case would provide a hydraulic conductivity representative of the aquifer if the assumption that the disturbed zone creates negligible flow resistance is correct.

Derivation of the installation factor is based on the case of a well point or hole extended in uniform sediment. In this case the flow rate (q) is expressed as follows equation 5;

$$q = \frac{2\pi LKH}{ln\left[\frac{L}{D} + \sqrt{1+\left(\frac{L}{D}\right)^2}\right]} \tag{5}$$

where

$q$ = flow rate $[L^3/T]$

L = length of the test zone [L]

H = initial head (Ho) at t = 0 [L]

D = diameter of the test zone [L]

K = hydraulic conductivity [L/T]

The variable D provides for the different cases described above. For case 1, D is the actual diameter of the well screen. The hydraulic conductivity in the disturbed zone is assumed to be equal to the aquifer. For case 3, D reflects the outside diameter of borehole and assumes that minimal caving-in of the borehole has occurred. This is optimistic because the extent of borehole failure below the water table is unknown. Combining equation 5 and 6,

$$q = FKH \tag{6}$$

where F is referred to as the shape factor by Hvorslev and is more clearly expressed by equation 7.

$$F = \frac{2\pi L}{ln\left[\frac{L}{D} + \sqrt{1+\left(\frac{L}{D}\right)^2}\right]} \tag{7}$$

Combining equation 6 and 8,

$$q = A\ dy/dt \tag{8}$$

where A= $\pi\ r_c^2$ is the cross sectional area of the casing or riser pipe, yields equations 9 and 10.

$$\frac{F}{A} = \frac{1}{KH}\ dy/dt \tag{9}$$

$$K = \frac{A}{FH}\ dy/dt \tag{10}$$

where F/A is the installation factor. Thus it can be seen from equation 10 that the hydraulic conductivity is inversely proportional to the installation factor and F is a function of the length (L) of the test interval and the diameter (D) of the test zone.

## 13.4 Packer-Slug Tests

The different conditions considered in the analysis of the field data were outlined earlier, however, the resultant installation factors require further elaboration. Although three conditions have been presented, for clarity, only two have been plotted. These two factors; one for the partially clogged well screen and the other for the unclogged well screen and the infinitely permeable disturbed zone, may be considered the extreme limits in an augered hole.

The first case assumes that the well screen was partially clogged or bridged. The diameter of the testing interval in this case is 5.14 cm, which is the inside diameter of the well screen, with standpipe radius ($r_c$) = 1.32 cm. Applying equation 7 and dividing by the cross sectional area of the standpipe gives F/A = 6.54. In the second case, D is set at 18.10 cm, which is the diameter of the augered hole, and $r_c$ is as before. This case yields F/A = 14.18. In the intermediate case, the diameter of the testing interval was set at 6.03 cm, the outside diameter of the well screen. In this case F/A = 7.07.

The use of the different installation factors in the Hvorslev analyses simply shifts the hydraulic conductivities to lower values when larger F/A factors are used. This results in approximately half an order of magnitude decrease in the mean hydraulic conductivity when F/A = 14.18 is used compared to F/A = 6.54.

## 13.5 Comparison of Packer-Slug Tests and Permeameter Results

The permeameter tests that were correlated and averaged over 20 cm intervals to coincide with the intervals used in the packer-slug tests are profiled in figures 8 and 9 for sites C-1/T-1 and C-5/T-5, respectively. The correlation coefficient computed for all packer-slug test and permeameter values is 0.3732. The packer-slug tests values for F/A=6.54 and 14.18 are also profiled and represent the minimum and maximum test diameters, respectively. Although the 20 cm average permeameter profiles lack the hydraulic conductivity resolution of the 5 cm hydraulic conductivity profiles, the vertical variability in hydraulic conducivity is still evident compared to the packer-slug tests that do not show any hydraulic conductivities significanty below $10^{-3}$ cm/s range or above 5 x $10^{-3}$ cm/s. Examination of the comparative profiles, figures 10-12, shows that the range in hydraulic conductivity observed in the permeameter test profile is not adequately represented in the slug test profiles. Changes in the installation factor simply shifts the profiled to lower ranges. Figure 12 shows that the nearly 200 hydraulic conductivities plotted although widely scattered across the permeameter field of four orders of magnitude, are largely restricted to 1.5 orders of magnitude in the packer-slug test field.

A comparison of the means presented in table 4 shows that for sites C-1/T-1 and C-5/T-5 a general trend can be observed for the arithmetic and harmonic means. These values show that for the arithmetic mean, the permeameter values are larger than the slug test values for F/A = 14.18 by a minimum of a factor of 3 to greater than an order of magnitude. The harmonic means show however that the slug test values are greater by approximately a factor of 6. No trend is observed in the geometric means for sites C-1 and C-5. At C-1 the permeameter tests are an 1.6 times greater that the slug tests whereas at C-5 the slug tests are 1.4 times greater than the permeameter tests.

## 13.6 Assessment of the Radius of Influence for Head Dissipation

A method developed by Bouwer and Rice, (1976) for the analysis of the slug test can be used to investigate the degree of influence excerted by the disturbed zone. Bouwer and Rice define the effective radius ($R_e$) in a slug test as the radial distance over which the head loss/gain is dissipated. This value is dependent on the geometry of the system. The effective radius was determined by an "electrical resistance network analog for different values of $r_w$, L, H, and D..." (Bouwer and Rice, page 424). The terms are defined below.

The assumptions in their study are "(1) drawdown of the water table around the well is negligible, (2) flow above the water table (in the capillary fringe) can be ignored, (3) head losses as the water enters the well (well losses) are negligible, and (4) the aquifer is homogenous and isotropic." It is also assumed that no water is released from storage. From this work an empirical equation for the effective radius ($R_e$) was derived, equation 11, and is applicable to unconfined aquifers with either completely or partially penetrating wells or packer-slug tests.

$$ln\, R_e = \left[ \frac{1.1}{ln(H/r_w)} + \frac{A+B\, ln\left[(D-H)/r_w\right]}{L/r_w} \right]^{-1} + ln r_w \qquad (11)$$

where

A & B are dimensionless coefficients that are a function of $L/r_w$ and determined from a graph presented by Bouwer and Rice , (1976).

L = length of the testing interval [L]

$r_w$ = radius of the well screen or the disturbed zone if this zone has a much higher hydraulic conductivity than the formation [L]

D = thickness of the aquifer [L]

H = depth to the bottom of the testing interval, L [L]

In order to ascertain $R_e$ in a well in which the hydraulic conductivity of the disturbed zone was lower than the formation equation 11 was applied to $r_w$ = 3.0 that includes only the outside diameter of the well. The length of the test interval (L) was set at 20 cm, the thickness of the aquifer (D) was selected for site C-1 and set at 20.26 m, and the depth to the base of the test interval (H) was set at 8 m. A is equal to 1.8 and B is equal to 0.24. These were determined from figure 3 in Bouwer and Rice, (1976), according to the ratio of $L/r_w$ This gives an effective radius of 12.96 cm and indicates that in a borehole cut to a diameter of 18.10 cm, the difference in the radius of influence for head dissipation is 3.96 cm. If this small zone is also disturbed due to caving or hole failure then the slug test is not evaluating the hydraulic conductivity of the aquifer but rather the disturbed zone.

# XIV

# SUMMARY OF CONCLUSIONS

The hydraulic conductivities derived from permeameter tests and the Hazen method are quite similar for each of the five study sites. Three of the sites show nearly identical geometric means. At the other sites the largest difference in the geometric means is a factor of two or three. The variability demonstrated by the permeameter tests spans four orders of magnitude from $10^{-5}$ to $10^{-2}$ cm/s in each of the five holes. The hydraulic conductivities derived from the Hazen method also exhibit this range in variability. These results support the interpretation that the hydraulic conductivities derived from the permeameter tests are representative of the aquifer and are not an artifact of the laboratory procedures.

The slug tests values do not, however, exhibit the large range in hydraulic conductivity shown by the permeameter or the Hazen methods. The slug test hydraulic conductivities cover at most 1.5 orders of magnitude from a low of approximately $5 \times 10^{-4}$ to a high of $10^{-3}$ cm/s for each hole. In the analysis of the slug test data, different installation factors (F/A) used to account for the geometric relationship of the well and the borehole do not affect the difference between the minimum and maximum values of hydraulic conductivities derived from the slug test but instead shifts the distribution uniformly to lower values when a larger installation factor is used.

The slug test values apparently represent the hydraulic conductivity in the disturbed zone around the well screen rather than the undisturbed aquifer beyond the borehole. As a consequence, the slug test commonly overestimates the hydraulic conductivity in zones with a hydraulic conductivity lower than about $10^{-3}$ cm/s and underestimates it in zones where the hydraulic conductivity is greater than about $5 \times 10^{-3}$ cm/s.

The geometric mean from the slug tests and the permeameter tests exhibit close agreement. At site C-1, the permeameter tests are an average 1.3 times greater than the slug tests whereas at C-5, the slug test $K_G$'s are an average of 1.6 times greater than the permeameter tests.

The effective radius calculation shows that the radius of influence for head dissipation from the well screen extends only about 4 cm beyond the calculated borehole diameter based on the auger blade diameter. At some depths the zone of disturbance due to caving should probably extend beyond the diameter of the auger. It is concluded that the results from the slug tests represent a commingled response of the disturbed zone and the aquifer. Therefore, for the slug tests to yield accurate results of aquifer hydraulic conductivity beyond the disturbed zone it would be necessary to know the hydraulic conductivity of the mixed sediment in the disturbed zone. However, because the extent of caving is unknown and the backfill constitutes a mix of sediment encountered during drilling, determination of the hydraulic conductivity in this disturbed zone is generally not feasible. It is suggested that alternative installations procedures be considered such as drilling to the top of the proposed screen depth and installing the well screen by percussion or jetting to limit the disturbed zone around the well screen.

## XV

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Table 1. Hydraulic conductivities (cm/s) from permeameter tests

| MEANS | C1 | C2 | C3<br>(5 cm intervals) | C4 | C5 |
|---|---|---|---|---|---|
| Mean($\bar{x}$) | $1.02\text{x}10^{-2}$ | $5.51\text{x}10^{-3}$ | $3.62\text{x}10^{-3}$ | $2.70\text{x}10^{-3}$ | $2.04\text{x}10^{-3}$ |
| Geometric $K_G$ | $2.84\text{x}10^{-3}$ | $1.24\text{x}10^{-3}$ | $1.62\text{x}10^{-3}$ | $8.85\text{x}10^{-4}$ | $4.70\text{x}10^{-4}$ |
| Arithmetic $K_A$ | $3.89\text{x}10^{-2}$ | $7.47\text{x}10^{-3}$ | $6.21\text{x}10^{-3}$ | $4.33\text{x}10^{-3}$ | $2.50\text{x}10^{-3}$ |
| Harmonic $K_H$ | $2.08\text{x}10^{-4}$ | $2.04\text{x}10^{-4}$ | $4.21\text{x}10^{-4}$ | $1.81\text{x}10^{-4}$ | $8.81\text{x}10^{-5}$ |
| Number of Values | 231 | 171 | 158 | 229 | 164 |

| MEANS | C1 | C2 | C3<br>(20 cm averages) | C4 | C5 |
|---|---|---|---|---|---|
| Mean($\bar{X}$) | $1.22\text{x}10^{-2}$ | $4.88\text{x}10^{-3}$ | $2.96\text{x}10^{-3}$ | $2.91\text{x}10^{-3}$ | $2.04\text{x}10^{-3}$ |
| Geometric $K_G$ | $4.30\text{x}10^{-3}$ | $1.28\text{x}10^{-3}$ | $1.21\text{x}10^{-3}$ | $1.47\text{x}10^{-3}$ | $5.80\text{x}10^{-4}$ |
| Arithmetic $K_A$ | $4.16\text{x}10^{-2}$ | $5.88\text{x}10^{-3}$ | $4.16\text{x}10^{-3}$ | $3.51\text{x}10^{-3}$ | $2.41\text{x}10^{-3}$ |
| Harmonic $K_H$ | $4.44\text{x}10^{-4}$ | $2.80\text{x}10^{-4}$ | $3.54\text{x}10^{-4}$ | $6.19\text{x}10^{-4}$ | $1.40\text{x}10^{-4}$ |
| Number of Values | 49 | 35 | 26 | 47 | 37 |

Table 2a. Hydraulic Conductivities (cm/s) from Hazen Method

| Means | C-1 | C-2 | C-3 | C-4 | C-5 |
|---|---|---|---|---|---|
| Mean ($\bar{X}$) | $9.25 \times 10^{-2}$ | $3.03 \times 10^{-1}$ | $3.21 \times 10^{-3}$ | $2.50 \times 10^{-3}$ | $3.83 \times 10^{-3}$ |
| Geometric $K_G$ | $4.25 \times 10^{-3}$ | $3.29 \times 10^{-3}$ | $1.33 \times 10^{-3}$ | $6.10 \times 10^{-4}$ | $1.54 \times 10^{-3}$ |
| Arithmetic $K_A$ | $1.39 \times 10^{-1}$ | $1.88 \times 10^{-1}$ | $7.1 \times 10^{-3}$ | $8.78 \times 10^{-3}$ | $5.23 \times 10^{-3}$ |
| Harmonic $K_H$ | $1.3 \times 10^{-4}$ | $5.75 \times 10^{-5}$ | $2.50 \times 10^{-4}$ | $4.25 \times 10^{-5}$ | $4.52 \times 10^{-4}$ |
| Number of Values | 53 | 35 | 32 | 45 | 38 |

Table 2b. Hydraulic Conductivities (cm/s) from permeameter tests correlated with those used in the Hazen Method

| Means | C-1 | C-2 | C-3 | C-4 | C-5 |
|---|---|---|---|---|---|
| Mean ($\bar{X}$) | $1.13 \times 10^{-2}$ | $5.90 \times 10^{-3}$ | $3.54 \times 10^{-3}$ | $2.91 \times 10^{-3}$ | $3.26 \times 10^{-3}$ |
| Geometric $K_G$ | $3.14 \times 10^{-3}$ | $1.05 \times 10^{-3}$ | $1.20 \times 10^{-3}$ | $7.17 \times 10^{-4}$ | $7.96 \times 10^{-4}$ |
| Arithmetic $K_A$ | $3.52 \times 10^{-2}$ | $8.82 \times 10^{-3}$ | $7.89 \times 10^{-3}$ | $6.82 \times 10^{-3}$ | $6.08 \times 10^{-3}$ |
| Harmonic $K_H$ | $2.80 \times 10^{-4}$ | $1.25 \times 10^{-4}$ | $1.84 \times 10^{-4}$ | $7.54 \times 10^{-5}$ | $1.04 \times 10^{-4}$ |
| Number of Values | 53 | 35 | 32 | 45 | 38 |

Table 3. Hydraulic conductivities (cm/s) from packer slug tests

| MEANS | T1 | T2 | T3 (F/A = 6.54) | T4 | T5 |
|---|---|---|---|---|---|
| Mean ($\bar{x}$) | $6.50\times10^{-3}$ | $4.03\times10^{-3}$ | $5.19\times10^{-3}$ | $3.54\times10^{-3}$ | $1.89\times10^{-3}$ |
| Geometric $K_G$ | $5.98\times10^{-3}$ | $2.25\times10^{-3}$ | $4.59\times10^{-3}$ | $2.94\times10^{-3}$ | $1.82\times10^{-3}$ |
| Arithmetic $K_A$ | $6.51\times10^{-3}$ | $3.71\times10^{-3}$ | $5.29\times10^{-3}$ | $3.64\times10^{-3}$ | $1.89\times10^{-3}$ |
| Harmonic $K_H$ | $5.48\times10^{-3}$ | $1.36\times10^{-3}$ | $3.99\times10^{-3}$ | $2.37\times10^{-3}$ | $1.75\times10^{-3}$ |
| Number of Values | 64 | 47 | 35 | 49 | 52 |

| MEANS | T1 | T2 | T3 (F/A = 7.07) | T4 | T5 |
|---|---|---|---|---|---|
| Mean ($\bar{x}$) | $5.99\times10^{-3}$ | $1.86\times10^{-3}$ | $2.4\times10^{-3}$ | $1.63\times10^{-3}$ | $1.75\times10^{-3}$ |
| Geometric $K_G$ | $5.50\times10^{-3}$ | $1.04\times10^{-3}$ | $2.12\times10^{-3}$ | $1.36\times10^{-3}$ | $1.68\times10^{-3}$ |
| Arithmetic $K_A$ | $6.01\times10^{-3}$ | $1.71\times10^{-3}$ | $2.44\times10^{-3}$ | $1.68\times10^{-3}$ | $1.75\times10^{-3}$ |
| Harmonic $K_H$ | $5.03\times10^{-3}$ | $6.3\times10^{-4}$ | $1.84\times10^{-3}$ | $1.09\times10^{-3}$ | $1.62\times10^{-3}$ |
| Number of Values | 64 | 47 | 35 | 49 | 52 |

| MEANS | T1 | T2 | T3 (F/A = 14.18) | T4 | T5 |
|---|---|---|---|---|---|
| Mean ($\bar{x}$) | $2.99\times10^{-3}$ | $3.73\times10^{-3}$ | $4.80\times10^{-3}$ | $3.28\times10^{-3}$ | $8.71\times10^{-4}$ |
| Geometric $K_G$ | $2.74\times10^{-3}$ | $2.08\times10^{-3}$ | $4.25\times10^{-3}$ | $2.72\times10^{-3}$ | $8.39\times10^{-4}$ |
| Arithmetic $K_A$ | $3\times10^{-3}$ | $3.43\times10^{-3}$ | $4.89\times10^{-3}$ | $3.37\times10^{-3}$ | $8.71\times10^{-4}$ |
| Harmonic $K_H$ | $2.51\times10^{-3}$ | $1.26\times10^{-3}$ | $3.69\times10^{-3}$ | $2.2\times10^{-3}$ | $8.08\times10^{-4}$ |
| Number of Values | 64 | 47 | 35 | 49 | 52 |

Table 4. Hydraulic conductivity (cm/s) comparison of means for permeameter tests and packer slug tests

SITE C/T-1

| MEANS | C1<br>(5 cm tests) | C1<br>(20 cm averages) | T1<br>(F/A=6.54) | T1<br>(F/A=7.07) | T1<br>(F/A=14.18) |
|---|---|---|---|---|---|
| Mean ($\bar{X}$) | $1.02 \times 10^{-2}$ | $1.22 \times 10^{-2}$ | $6.50 \times 10^{-3}$ | $5.99 \times 10^{-3}$ | $2.99 \times 10^{-3}$ |
| Geometric ($K_G$) | $2.84 \times 10^{-3}$ | $4.30 \times 10^{-3}$ | $5.98 \times 10^{-3}$ | $5.50 \times 10^{-3}$ | $2.74 \times 10^{-3}$ |
| Arithmetic ($K_A$) | $3.89 \times 10^{-2}$ | $4.16 \times 10^{-2}$ | $6.51 \times 10^{-3}$ | $6.01 \times 10^{-3}$ | $3.00 \times 10^{-3}$ |
| Harmonic ($K_H$) | $2.08 \times 10^{-4}$ | $4.44 \times 10^{-4}$ | $5.48 \times 10^{-3}$ | $5.03 \times 10^{-3}$ | $2.51 \times 10^{-3}$ |
| Number of Values | 231 | 49 | 64 | 64 | 64 |

SITE C/T-5

| MEANS | C5<br>(5 cm tests) | C5<br>(20 cm averages) | T5<br>(F/A=6.54) | T5<br>(F/A=7.07) | T5<br>(F/A=14.18) |
|---|---|---|---|---|---|
| Mean ($\bar{X}$) | $2.04 \times 10^{-3}$ | $2.04 \times 10^{-3}$ | $1.89 \times 10^{-3}$ | $1.75 \times 10^{-3}$ | $8.71 \times 10^{-4}$ |
| Geometric ($K_G$) | $4.70 \times 10^{-4}$ | $5.80 \times 10^{-4}$ | $1.82 \times 10^{-3}$ | $1.68 \times 10^{-3}$ | $8.39 \times 10^{-4}$ |
| Arithmetic ($K_A$) | $2.50 \times 10^{-3}$ | $2.41 \times 10^{-3}$ | $1.89 \times 10^{-3}$ | $1.75 \times 10^{-3}$ | $8.71 \times 10^{-4}$ |
| Harmonic ($K_H$) | $8.81 \times 10^{-5}$ | $1.40 \times 10^{-4}$ | $1.75 \times 10^{-3}$ | $1.62 \times 10^{-3}$ | $8.08 \times 10^{-4}$ |
| Number of Values | 164 | 37 | 52 | 52 | 52 |

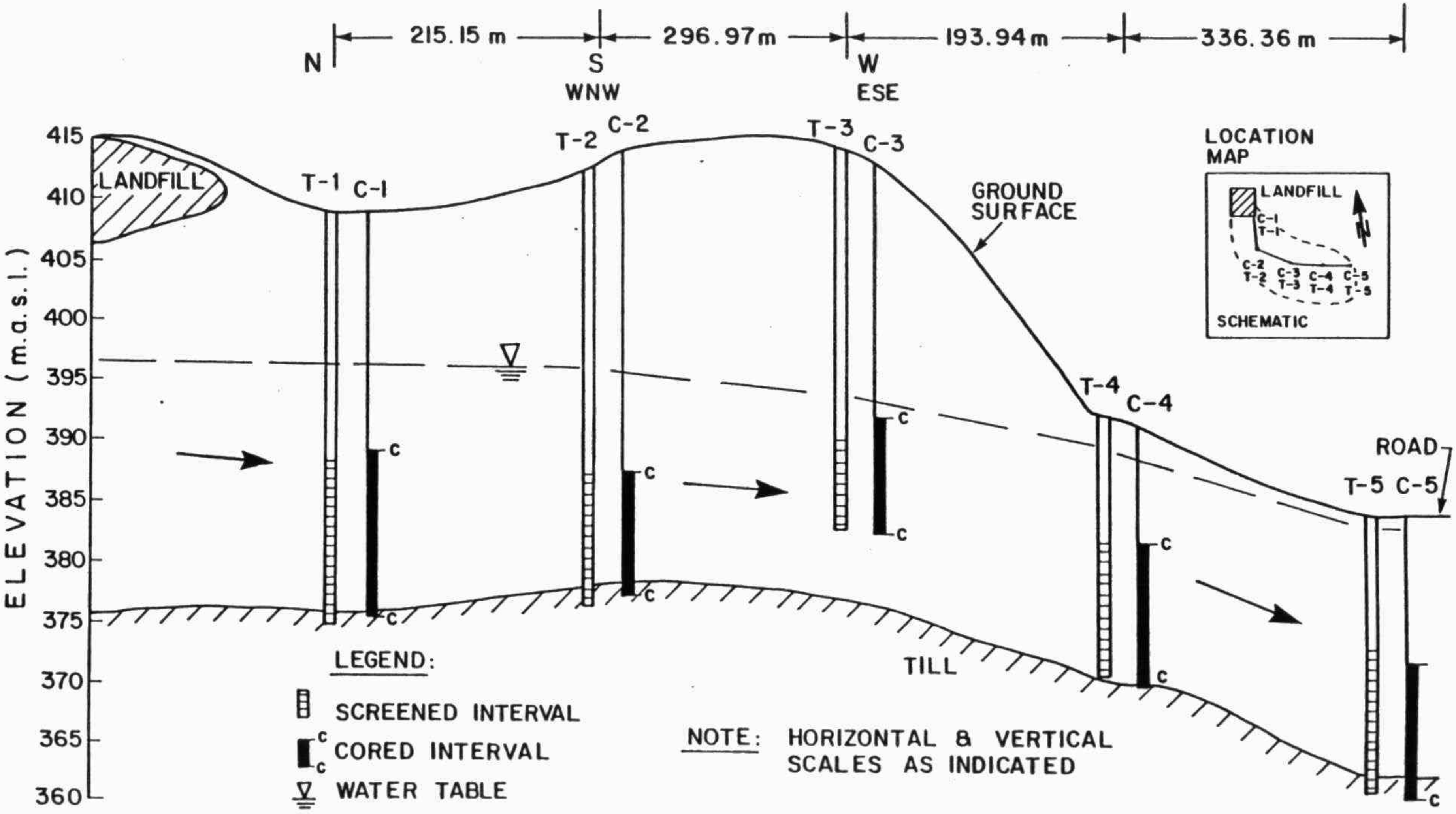

Figure 1: Schematic Cross Section of Study Area.

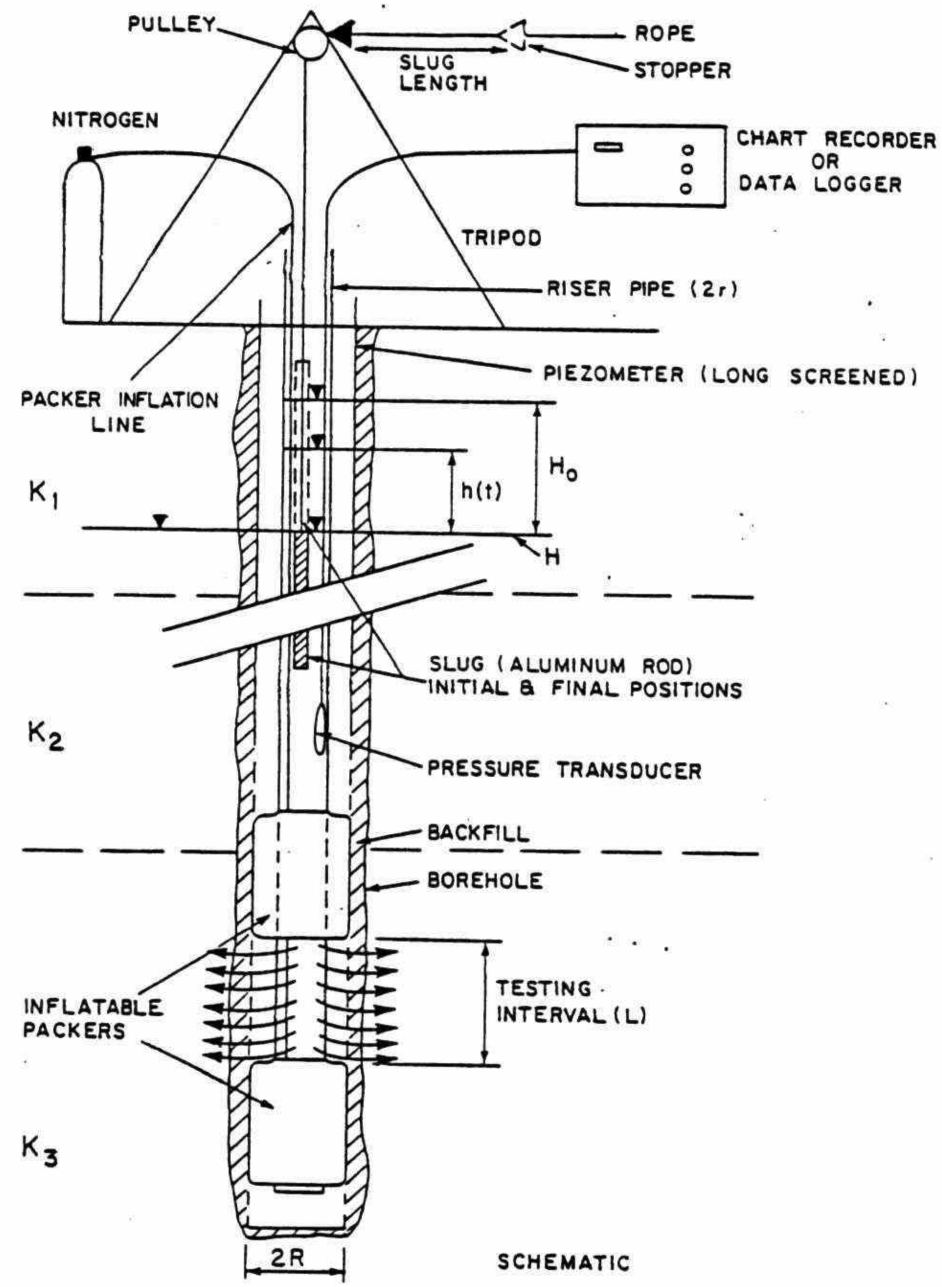

Figure 2: Double-Packer Pressure Transducer Slug Testing System for Falling Head Tests.

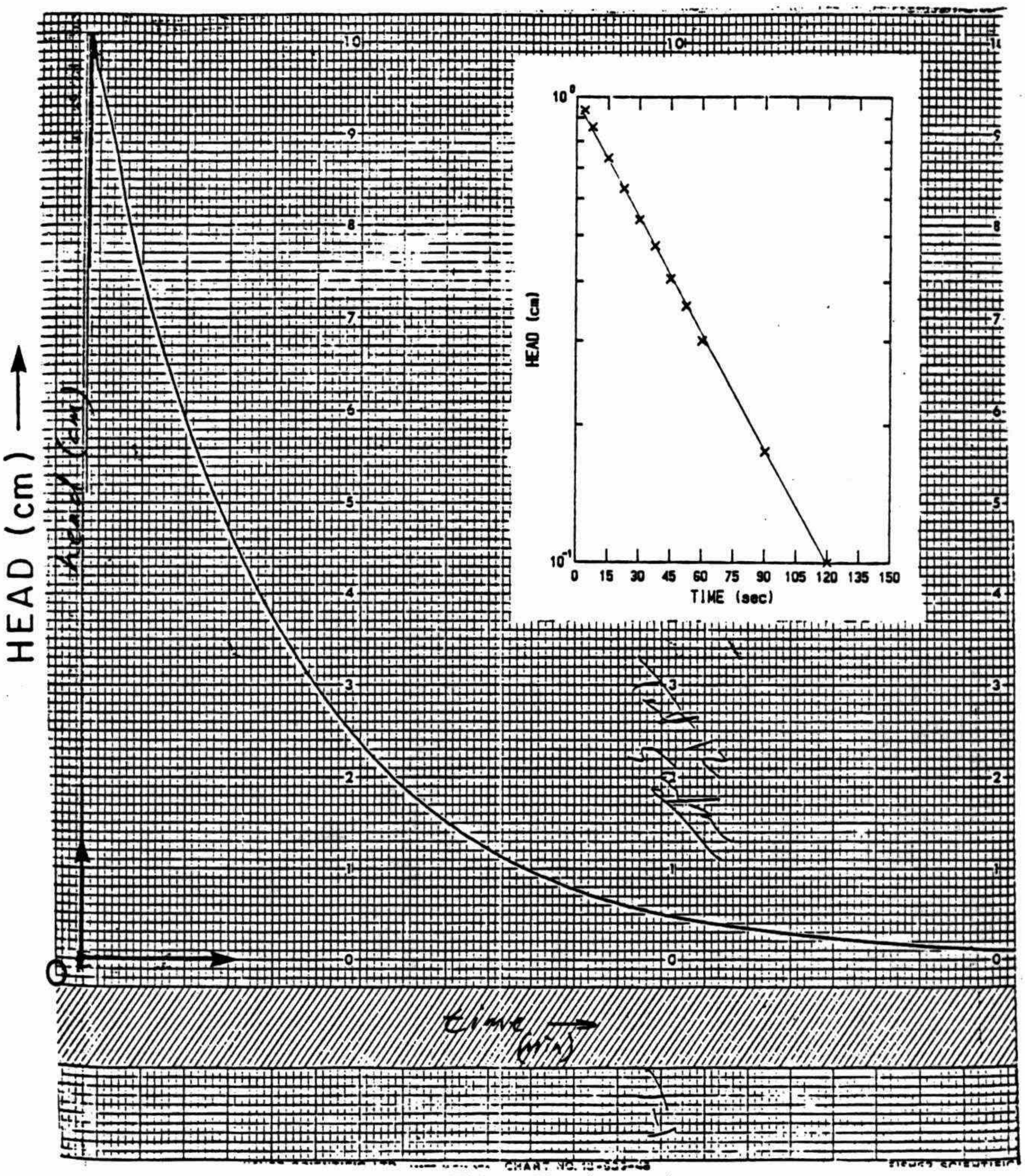

Figure 3: Sample Response Curve.

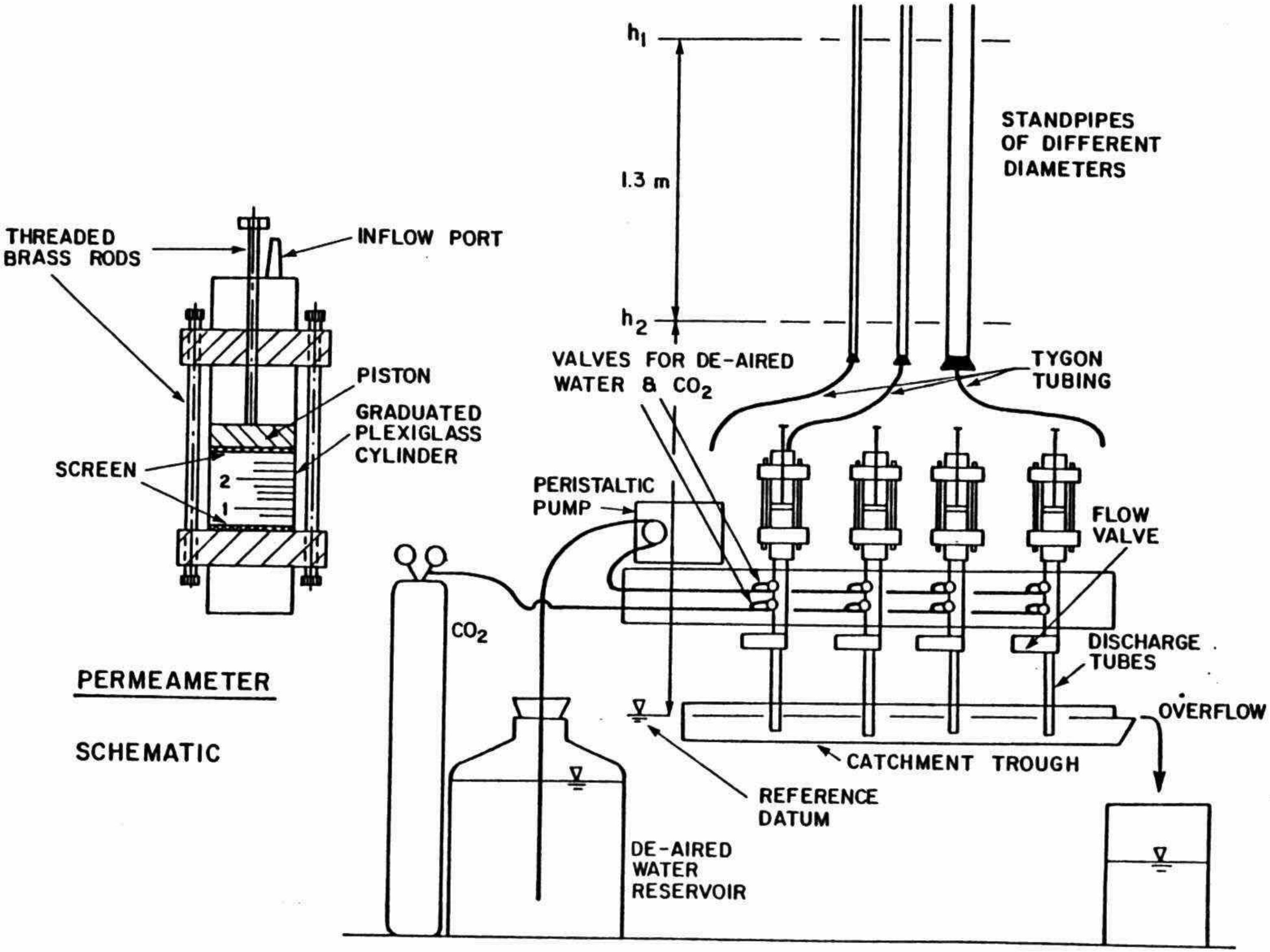

Figure 4: Falling Head Permeameter and Testing Station.

## PERMEAMETER RESULTS

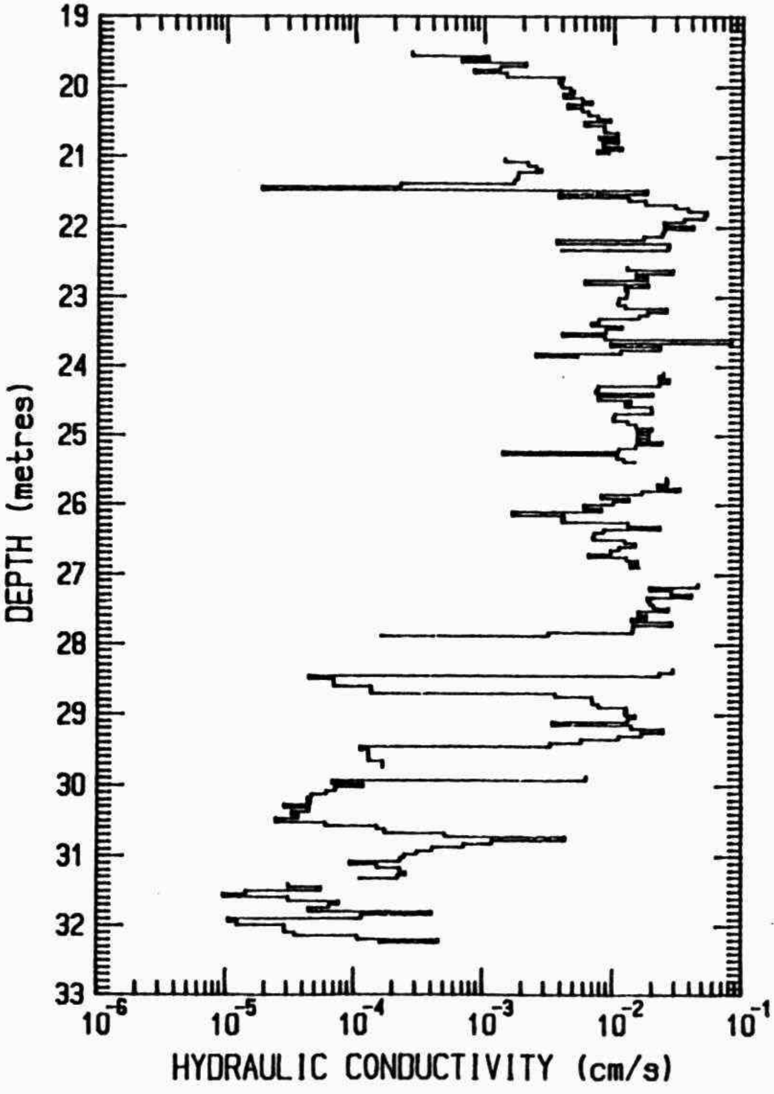

Figure 5: Hydraulic Conductivity Profile Site C-1.

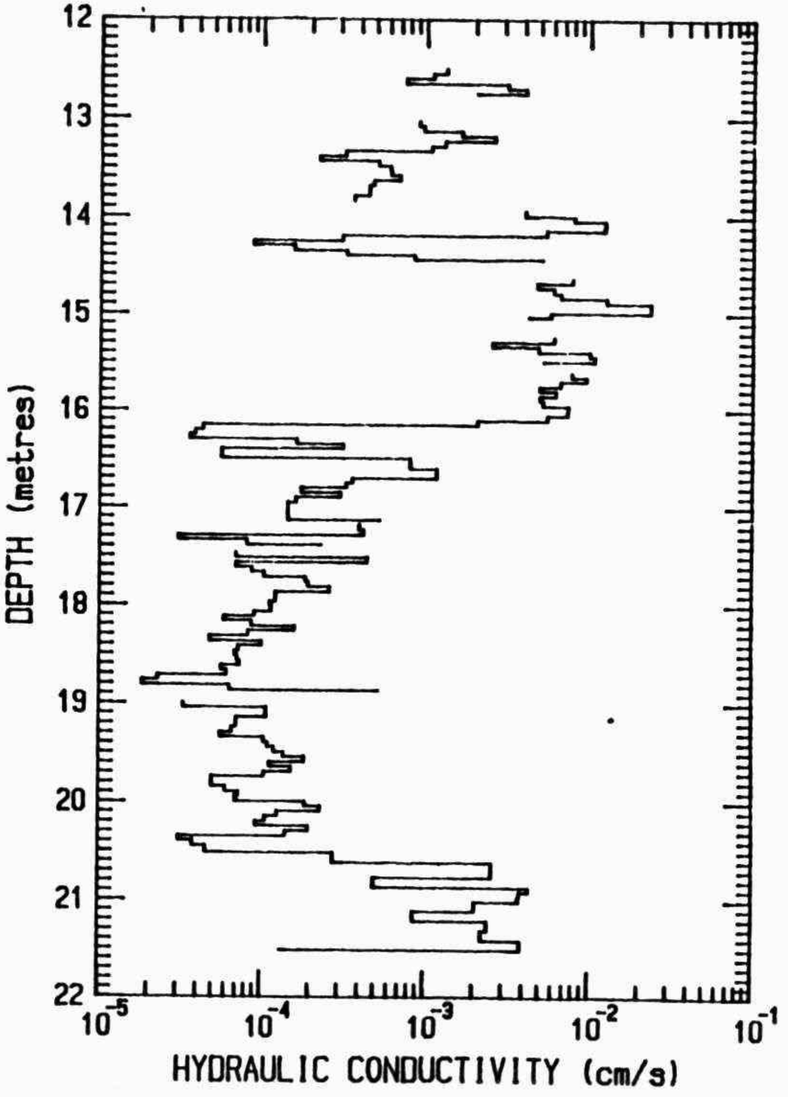

Figure 6: Hydraulic Conductivity Profile Site C-5.

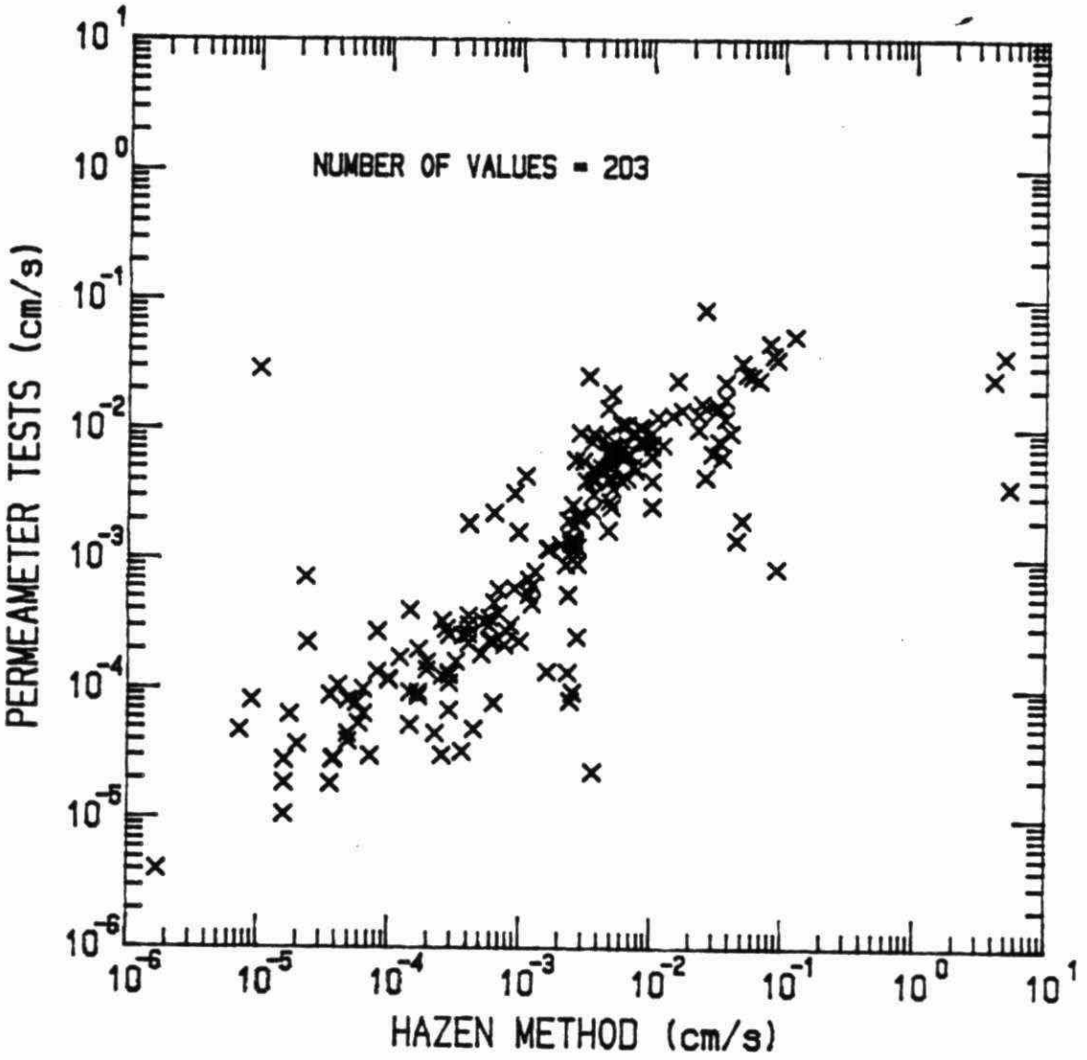

Figure 7: Comparison of Permeameter vs Hazen Hydraulic Conductivities Sites C-1 to C-5.

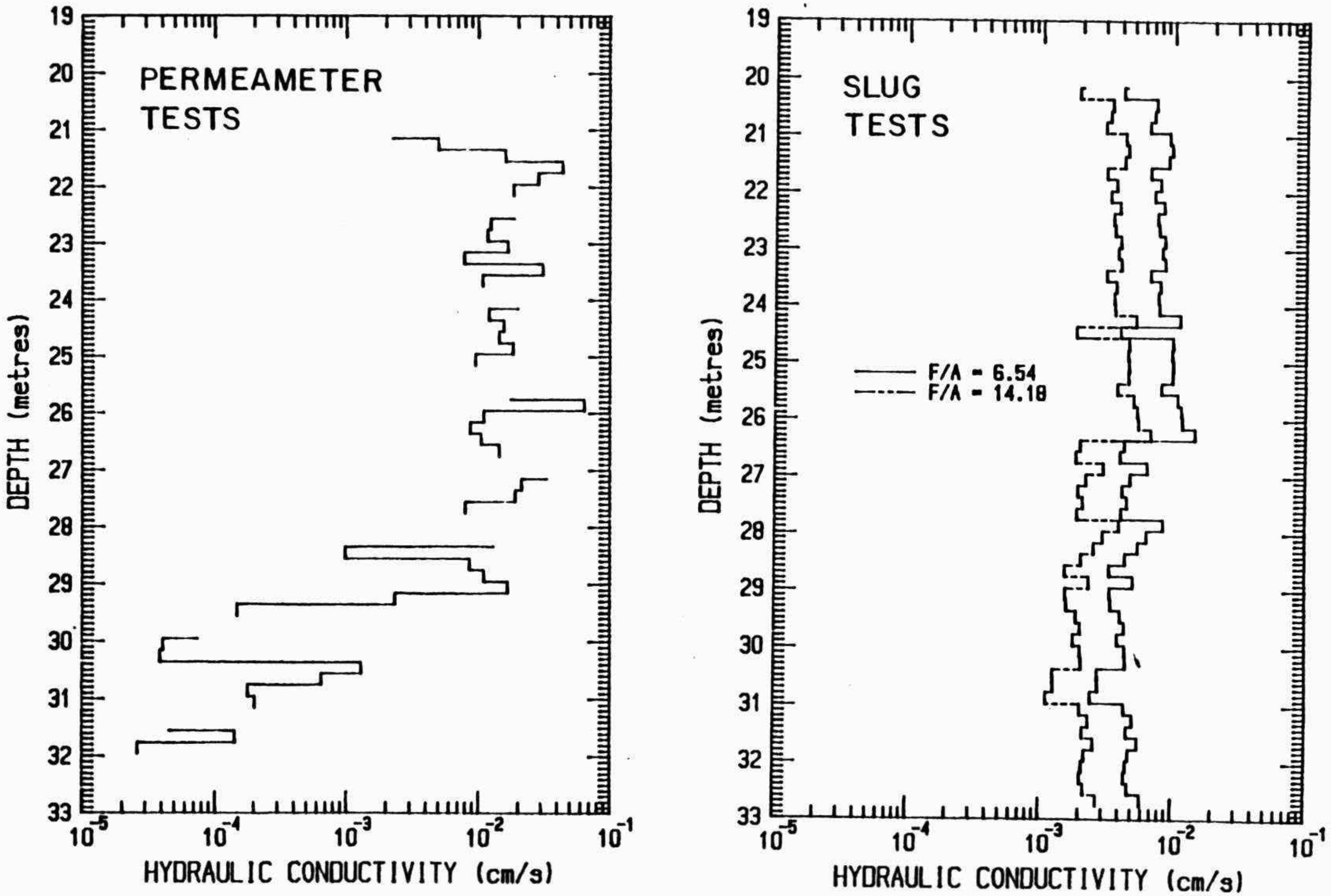

Figure 8: Hydraulic Conductivity Comparison Profiles for Sites C-1 and T-1. The profile for C-1 (left) is derived from 20 cm averages.

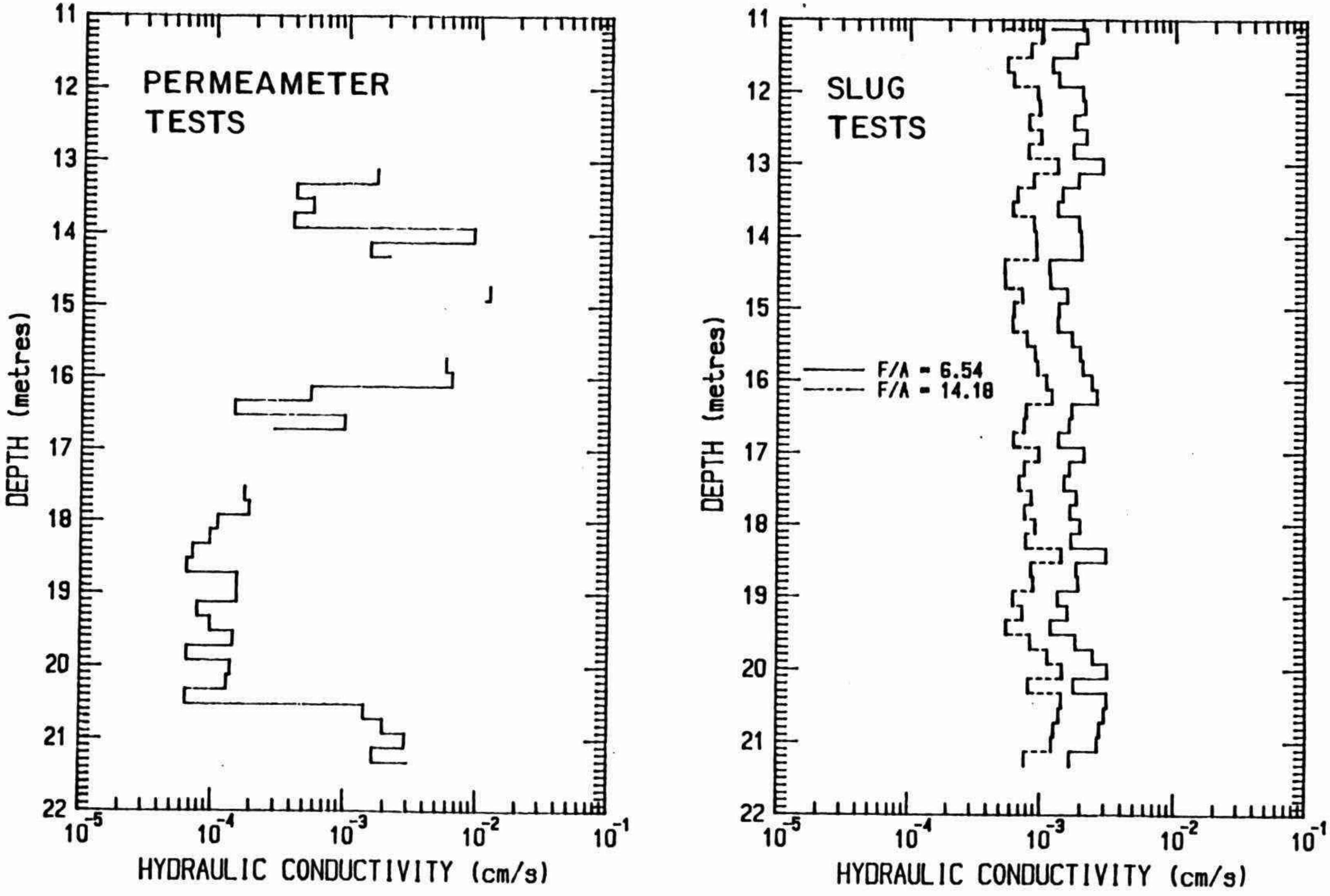

Figure 9: Hydraulic Conductivity Comparison Profiles for Sites C-5 and T-5.
The profile for C-5 (left) is derived from 20 cm averages.

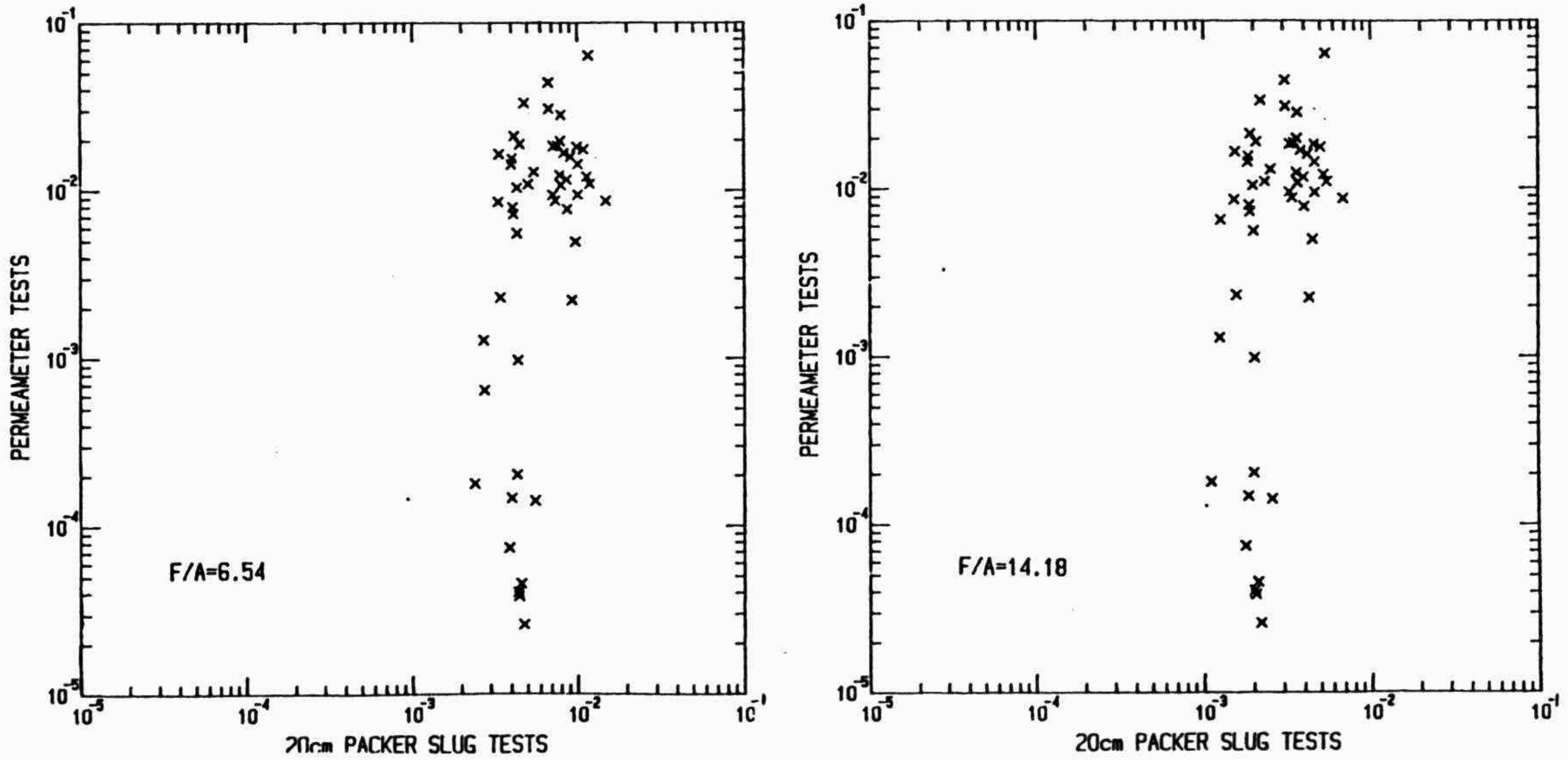

Figure 10a and b: Comparison of Permeameter vs Packer-Slug Test Hydraulic Conductivities for Sites C-1 and T-1. F/A = 6.54 in 10a (left) and F/A = 14.18 in 10b (ri[illegible].

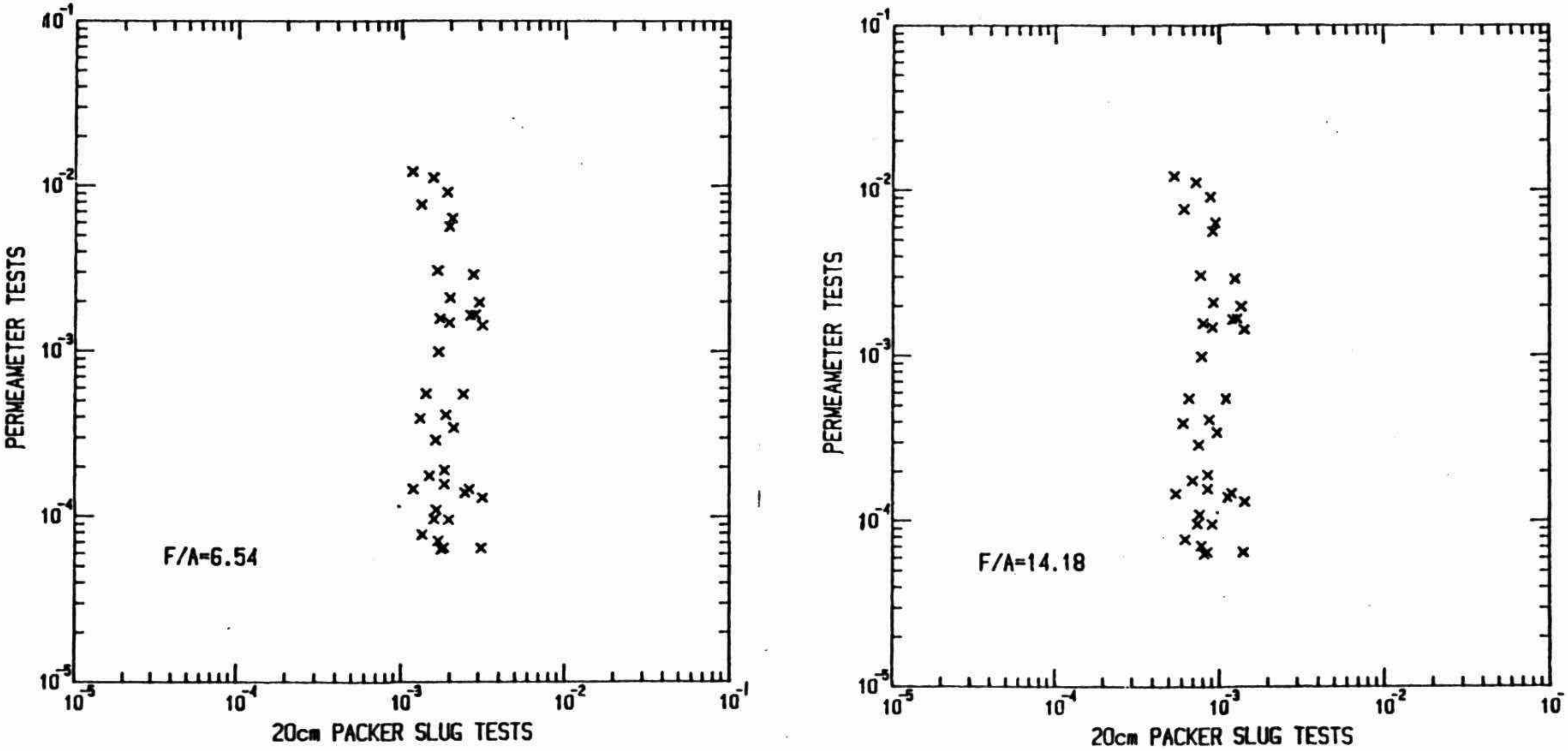

Figure 11a and b: Comparison of Permeameter vs Packer-Slug Test Hydraulic Conductivities for Sites C-5 and T-5. F/A = 6.54 in 11a (left) and F/A = 14.18 in 11b (right).

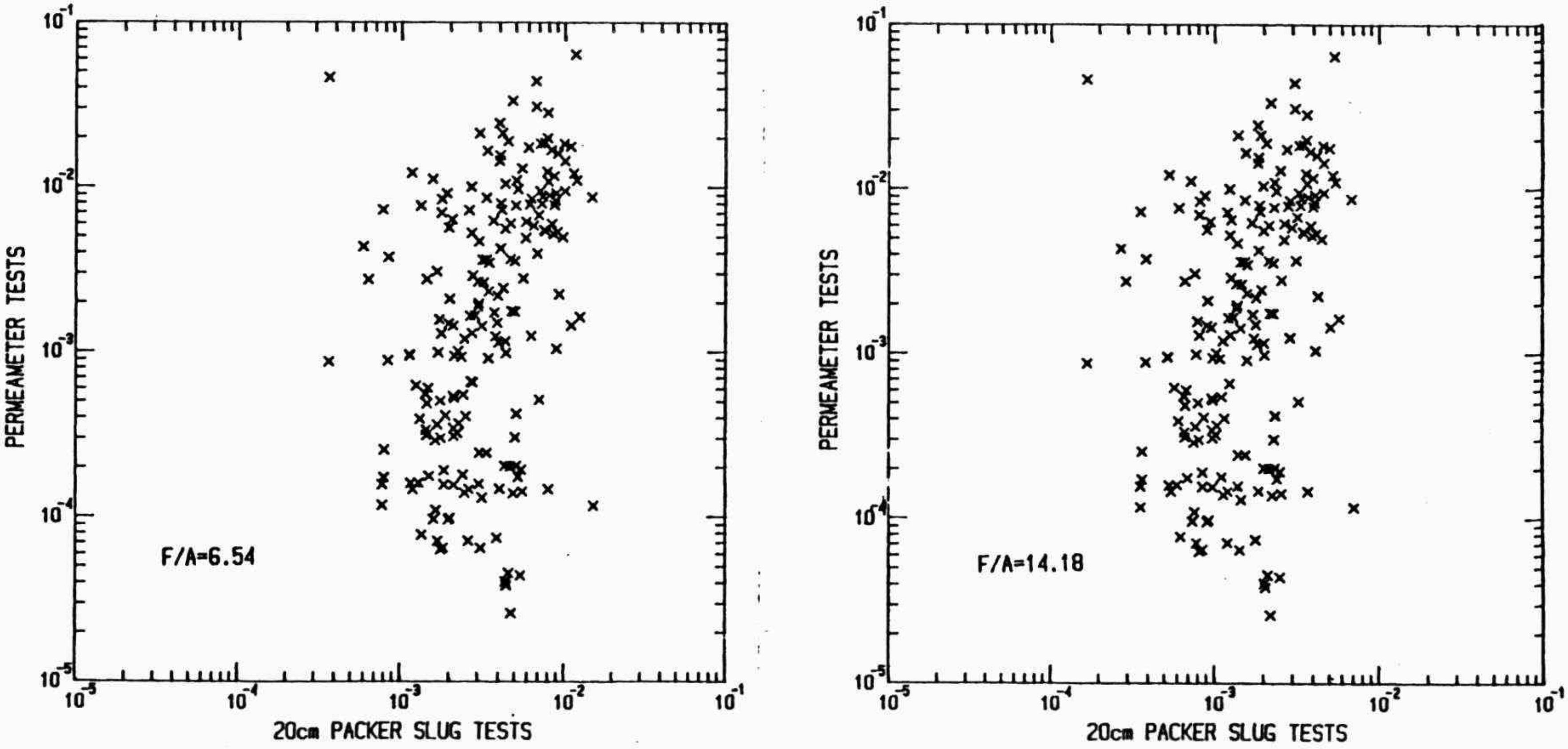

Figure 12a and b: Comparison of Permeameter vs Packer-Slug Test Hydraulic Conductivities for Sites C-1 to C-5 and T-1 to T-5. F/A = 6.54 in 12a (left) and F/A = 14[redacted] in [redacted] (r[redacted]).

## Appendix A

# HYDRAULIC CONDUCTIVITY DATA

## A.1 Permeameter Values for 5 cm Tests.

```
C1  HYDRAULIC CONDUCTIVITIES
231
19.51 2.74E-4
19.56 1.08E-3
19.61 6.68E-4
19.66 2.09E-3
19.71 1.32E-3
19.76 8.30E-4
19.81 1.48E-3
19.86 4.11E-3
19.91 3.80E-3
19.96 3.95E-3
20.01 4.62E-3
20.06 4.93E-3
20.11 4.11E-3
20.16 5.67E-3
20.21 6.69E-3
20.26 4.40E-3
20.31 5.68E-3
20.36 6.33E-3
20.41 7.48E-3
20.46 9.34E-3
20.51 5.94E-3
20.56 8.45E-3
20.61 8.37E-3
20.66 1.06E-2
20.71 7.62E-3
20.76 1.08E-2
20.81 8.22E-3
20.86 1.15E-2
20.91 7.39E-3
20.96 9.27E-3
21.03 1.43E-3
21.08 2.18E-3
21.13 2.54E-3
21.18 2.78E-3
21.23 1.82E-3
21.28 1.81E-3
21.33 1.70E-3
21.38 2.25E-4
21.43 1.85E-5
21.48 1.80E-2
21.53 3.79E-3
21.58 1.29E-2
21.63 1.75E-2
21.68 2.97E-2
21.73 3.73E-2
21.78 5.30E-2
21.83 5.11E-2
21.88 3.47E-2
21.93 2.41E-2
21.98 4.15E-2
22.03 2.43E-2
22.08 2.35E-2
22.13 1.70E-2
22.18 3.67E-3
22.23 2.67E-2
22.28 2.61E-2
22.33 3.96E-3
22.56 1.27E-2
```

| | |
|---|---|
| 22.61 | 2.88E-2 |
| 22.66 | 1.48E-2 |
| 22.71 | 1.80E-2 |
| 22.76 | 5.99E-3 |
| 22.81 | 1.86E-2 |
| 22.86 | 1.23E-2 |
| 22.91 | 1.28E-2 |
| 22.96 | 1.27E-2 |
| 23.01 | 1.10E-2 |
| 23.06 | 1.08E-2 |
| 23.11 | 1.23E-2 |
| 23.16 | 2.55E-2 |
| 23.21 | 1.83E-2 |
| 23.26 | 1.58E-2 |
| 23.31 | 7.70E-3 |
| 23.36 | 6.70E-3 |
| 23.41 | 1.17E-2 |
| 23.46 | 8.81E-3 |
| 23.51 | 4.04E-3 |
| 23.56 | 8.52E-3 |
| 23.61 | 8.29E-2 |
| 23.66 | 9.48E-3 |
| 23.71 | 2.27E-2 |
| 23.76 | 1.14E-2 |
| 23.81 | 2.53E-3 |
| 23.86 | 5.35E-3 |
| 24.08 | 2.40E-2 |
| 24.13 | 2.23E-2 |
| 24.18 | 2.68E-2 |
| 24.23 | 2.26E-2 |
| 24.28 | 7.64E-3 |
| 24.33 | 7.30E-3 |
| 24.38 | 2.01E-2 |
| 24.43 | 7.64E-3 |
| 24.48 | 1.35E-2 |
| 24.53 | 1.24E-2 |
| 24.58 | 1.96E-2 |
| 24.63 | 1.99E-2 |
| 24.68 | 1.03E-2 |
| 24.73 | 9.92E-3 |
| 24.78 | 1.28E-2 |
| 24.83 | 1.48E-2 |
| 24.88 | 1.99E-2 |
| 24.93 | 1.54E-2 |
| 24.98 | 1.87E-2 |
| 25.03 | 1.53E-2 |
| 25.08 | 2.36E-2 |
| 25.13 | 1.49E-2 |
| 25.18 | 1.10E-2 |
| 25.23 | 1.40E-3 |
| 25.28 | 1.07E-2 |
| 25.33 | 1.20E-2 |
| 25.38 | 1.49E-2 |
| 25.60 | 2.57E-2 |
| 25.65 | 2.62E-2 |
| 25.70 | 2.17E-2 |
| 25.75 | 3.26E-2 |
| 25.80 | 1.66E-2 |
| 25.85 | 8.06E-3 |
| 25.90 | 1.33E-2 |

```
25.95 1.00E-2
26.00 5.89E-3
26.05 8.13E-3
26.10 1.66E-3
26.15 4.20E-3
26.20 4.04E-3
26.25 1.29E-2
26.30 2.29E-2
26.35 8.42E-3
26.40 7.08E-3
26.45 6.99E-3
26.50 1.23E-2
26.55 1.48E-2
26.60 1.11E-2
26.65 9.60E-3
26.70 6.49E-3
26.75 1.26E-2
26.80 1.54E-2
26.85 1.35E-2
26.90 1.59E-2
27.13 4.59E-2
27.18 1.91E-2
27.23 2.79E-2
27.28 4.09E-2
27.33 1.84E-2
27.38 1.91E-2
27.43 2.04E-2
27.48 2.67E-2
27.53 1.55E-2
27.58 1.81E-2
27.63 1.39E-2
27.68 2.83E-2
27.73 1.44E-2
27.78 1.42E-2
27.83 3.20E-3
27.88 1.64E-4
28.35 2.90E-2
28.40 2.28E-2
28.45 4.45E-5
28.50 6.99E-5
28.55 6.99E-5
28.60 1.35E-4
28.65 1.35E-4
28.70 3.60E-3
28.75 6.85E-3
28.80 6.97E-3
28.85 7.73E-3
28.90 1.28E-2
28.95 1.24E-2
29.00 1.49E-2
29.05 1.31E-2
29.10 3.44E-3
29.15 1.39E-2
29.20 2.44E-2
29.25 1.67E-2
29.30 1.12E-2
29.35 5.71E-3
29.40 3.34E-3
29.45 1.11E-4
29.50 1.29E-4
```

```
29.55 1.29E-4
29.60 1.29E-4
29.65 1.67E-4
29.70 1.67E-4
29.75 1.67E-4
29.87 6.26E-3
29.92 6.78E-5
29.97 1.18E-4
30.02 7.20E-5
30.07 6.13E-5
30.12 4.70E-5
30.17 4.34E-5
30.22 4.61E-5
30.27 2.85E-5
30.32 4.50E-5
30.37 3.24E-5
30.42 3.71E-5
30.47 2.45E-5
30.52 6.02E-5
30.57 1.50E-4
30.62 1.73E-4
30.67 5.02E-4
30.72 4.36E-3
30.77 1.18E-3
30.82 7.14E-4
30.87 4.04E-4
30.92 3.08E-4
30.97 2.46E-4
31.02 2.30E-4
31.07 9.26E-5
31.12 1.50E-4
31.17 2.28E-4
31.22 2.52E-4
31.27 2.20E-4
31.32 1.11E-4
31.39 3.07E-5
31.44 5.58E-5
31.49 1.43E-5
31.54 9.56E-6
31.59 3.08E-5
31.64 7.70E-5
31.69 6.53E-5
31.74 4.43E-5
31.79 3.99E-4
31.84 1.16E-4
31.89 1.05E-5
31.94 1.22E-5
31.99 2.91E-5
32.04 2.86E-5
32.09 3.44E-5
32.14 1.06E-4
32.19 4.54E-4
32.24 1.61E-4
```

```
C2  HYDRAULIC CONDUCTIVITIES
171
24.08 1.57E-2
24.13 2.04E-2
24.18 2.40E-2
24.23 2.44E-2
24.28 1.57E-2
24.33 1.77E-2
24.38 2.72E-2
24.43 3.08E-2
24.48 2.72E-2
24.53 2.62E-2
24.58 1.37E-2
24.63 1.82E-2
24.68 1.92E-2
24.73 1.65E-2
24.78 1.57E-2
24.83 1.03E-2
24.88 1.10E-2
24.93 8.65E-3
24.98 9.00E-3
25.03 5.48E-5
25.08 2.77E-5
25.13 5.91E-5
25.18 3.60E-5
25.23 4.41E-5
25.28 7.08E-5
25.33 7.44E-5
25.38 5.05E-4
25.43 1.79E-4
25.48 2.18E-4
25.60 3.09E-4
25.65 2.29E-3
25.70 4.37E-3
25.75 7.71E-3
25.80 1.27E-4
25.85 2.01E-4
25.90 3.70E-4
25.95 7.53E-4
26.00 7.63E-4
26.05 9.99E-4
26.10 4.93E-4
26.15 4.93E-4
26.20 1.75E-4
26.25 6.18E-4
26.30 8.35E-4
26.35 1.03E-3
26.40 1.56E-3
26.45 1.51E-3
26.50 2.34E-3
26.55 1.62E-3
26.60 2.86E-4
26.65 5.67E-4
26.70 1.18E-3
26.75 1.30E-3
26.80 7.26E-4
26.85 4.35E-4
26.90 2.00E-4
26.95 2.72E-4
27.00 3.29E-4
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```
27.13 9.37E-5
27.18 1.22E-4
27.23 1.02E-4
27.28 5.89E-5
27.33 1.16E-4
27.38 1.16E-4
27.43 2.40E-4
27.48 5.48E-4
27.53 1.18E-3
27.58 1.87E-3
27.63 2.96E-4
27.68 2.96E-4
27.73 3.51E-4
27.78 7.85E-5
27.83 2.44E-4
27.88 2.72E-4
27.93 6.83E-3
27.98 7.68E-3
28.03 9.36E-3
28.08 8.59E-3
28.13 6.06E-3
28.18 5.21E-3
28.23 4.54E-3
28.28 4.77E-3
28.33 5.24E-3
28.38 2.86E-3
28.43 1.34E-4
28.65 8.14E-5
28.70 1.47E-4
28.75 3.26E-4
28.80 1.38E-4
28.85 2.13E-4
28.90 9.83E-5
28.95 7.37E-5
29.00 8.68E-5
29.05 1.34E-4
29.10 6.26E-5
29.15 1.33E-4
29.20 3.00E-4
29.25 2.50E-4
29.30 7.73E-5
29.35 5.67E-3
29.40 4.95E-3
29.45 5.45E-3
29.50 4.72E-3
30.18 1.31E-4
30.23 1.16E-3
30.28 1.35E-3
30.33 5.11E-4
30.38 7.68E-4
30.43 7.12E-4
30.48 2.42E-4
30.53 2.42E-4
30.58 1.47E-4
30.63 2.17E-4
30.68 5.39E-5
30.73 2.69E-4
30.78 2.10E-3
30.83 1.85E-3
30.88 1.06E-3
```

```
30.93 1.40E-3
30.98 2.72E-3
31.03 2.58E-3
31.08 1.15E-3
31.13 9.83E-4
31.18 1.08E-3
31.23 3.98E-3
31.28 1.80E-3
31.33 1.41E-3
31.38 1.41E-3
31.43 3.59E-3
31.48 3.59E-3
31.53 3.59E-3
31.70 2.51E-4
31.75 2.51E-4
31.80 4.06E-4
31.85 4.06E-4
31.90 4.06E-4
31.95 4.68E-4
32.00 4.68E-4
32.05 4.68E-4
32.10 1.78E-3
32.15 1.78E-3
32.20 2.48E-3
32.25 8.785E-3
32.30 6.74E-3
32.35 6.10E-3
32.40 5.50E-3
32.45 5.21E-3
32.50 2.55E-3
32.55 1.46E-3
32.60 2.00E-3
32.65 3.16E-3
32.70 8.94E-3
32.75 2.35E-3
32.80 2.51E-3
32.85 2.51E-3
32.90 2.51E-3
32.95 8.40E-4
33.00 2.89E-3
33.05 3.33E-3
33.22 3.62E-2
33.27 5.23E-2
33.32 5.23E-2
33.37 4.48E-2
33.42 2.22E-2
33.47 2.92E-2
33.52 3.41E-2
33.57 1.64E-2
33.62 1.50E-2
33.67 2.22E-2
33.72 2.31E-2
33.77 2.24E-4
```

```
C3  HYDRAULIC CONDUCTIVITIES
158
22.40 6.39E-3
22.45 5.41E-3
22.50 4.56E-3
22.55 4.10E-3
22.60 3.52E-3
22.65 3.90E-3
22.70 9.70E-3
22.75 4.82E-3
22.80 5.79E-3
22.85 5.07E-3
22.90 4.73E-3
22.95 5.17E-3
23.00 1.45E-2
23.05 1.96E-3
23.10 1.74E-3
23.15 2.30E-5
23.20 4.20E-3
23.25 5.66E-3
23.30 5.17E-3
23.35 5.24E-3
23.40 5.05E-3
23.45 5.25E-3
23.50 5.88E-3
23.55 5.84E-3
23.60 6.62E-3
23.93 5.01E-3
23.98 5.57E-3
24.03 5.12E-3
24.08 4.88E-3
24.13 5.22E-3
24.18 4.86E-3
24.23 5.92E-3
24.28 6.38E-3
24.33 6.02E-3
24.38 5.68E-3
24.43 5.04E-3
24.48 6.88E-3
24.53 6.45E-3
24.58 6.38E-3
24.63 5.31E-3
24.68 6.00E-3
24.73 5.35E-3
24.78 6.05E-3
24.83 5.63E-3
24.88 6.32E-3
24.93 5.18E-3
24.98 5.42E-3
25.03 6.16E-3
25.08 5.42E-3
25.13 5.80E-3
25.18 5.34E-3
25.45 7.57E-3
25.50 8.14E-3
25.55 8.00E-3
25.60 8.48E-3
25.65 8.61E-3
25.70 8.11E-3
25.75 8.36E-3
```

| | |
|---|---|
| 25.80 | 7.34E-3 |
| 25.85 | 8.00E-3 |
| 25.90 | 8.40E-3 |
| 25.95 | 9.08E-3 |
| 26.00 | 7.95E-3 |
| 26.05 | 8.63E-3 |
| 26.10 | 7.96E-3 |
| 26.15 | 8.82E-3 |
| 26.20 | 7.19E-3 |
| 26.25 | 7.64E-3 |
| 26.30 | 7.21E-3 |
| 26.35 | 5.97E-3 |
| 26.40 | 5.26E-3 |
| 26.45 | 5.58E-3 |
| 26.50 | 5.74E-3 |
| 26.55 | 5.06E-3 |
| 26.60 | 5.48E-3 |
| 26.65 | 5.19E-3 |
| 26.70 | 5.72E-3 |
| 26.75 | 5.20E-3 |
| 26.97 | 1.24E-3 |
| 27.02 | 4.92E-3 |
| 27.07 | 5.83E-3 |
| 27.12 | 5.22E-3 |
| 27.17 | 4.06E-3 |
| 27.22 | 3.01E-3 |
| 27.27 | 1.58E-3 |
| 27.32 | 9.08E-4 |
| 27.37 | 1.71E-3 |
| 27.42 | 1.97E-3 |
| 27.47 | 2.32E-3 |
| 27.52 | 2.23E-3 |
| 27.57 | 1.63E-3 |
| 27.62 | 5.96E-4 |
| 27.67 | 9.88E-5 |
| 27.72 | 5.32E-4 |
| 27.77 | 2.94E-4 |
| 27.82 | 2.22E-4 |
| 27.87 | 2.44E-4 |
| 27.92 | 2.86E-4 |
| 28.50 | 1.32E-4 |
| 28.55 | 1.16E-4 |
| 28.60 | 1.84E-4 |
| 28.65 | 1.99E-4 |
| 28.70 | 2.60E-4 |
| 28.75 | 2.68E-4 |
| 28.80 | 2.97E-4 |
| 28.85 | 3.78E-4 |
| 28.90 | 2.47E-4 |
| 28.95 | 3.27E-4 |
| 29.00 | 5.21E-4 |
| 29.05 | 3.77E-4 |
| 29.10 | 2.82E-4 |
| 29.15 | 4.10E-4 |
| 29.20 | 5.55E-4 |
| 29.25 | 6.92E-4 |
| 29.30 | 6.28E-4 |
| 29.35 | 6.20E-4 |
| 29.40 | 2.19E-4 |
| 29.45 | 1.60E-4 |

```
29.50 6.05E-5
29.55 7.97E-5
29.60 8.78E-5
29.65 5.74E-5
29.70 2.83E-5
29.75 1.72E-4
29.80 3.56E-4
29.85 2.54E-4
30.02 2.01E-4
30.07 1.55E-4
30.12 1.52E-4
30.17 1.31E-4
30.22 1.18E-4
30.40 8.18E-5
30.45 7.19E-5
30.50 4.45E-4
30.55 8.77E-4
30.60 5.45E-4
30.65 1.90E-4
30.70 2.24E-3
30.75 1.58E-3
30.80 3.00E-4
30.85 8.29E-5
30.90 8.34E-5
30.95 6.30E-5
31.00 6.68E-5
31.05 3.65E-4
31.10 4.97E-4
31.15 5.69E-4
31.20 8.10E-4
31.25 3.14E-3
31.30 2.96E-3
31.35 1.74E-3
31.40 4.97E-3
31.45 4.97E-3
31.50 4.85E-3
31.55 5.53E-3
31.60 4.70E-3
31.65 9.14E-3
31.70 1.98E-3
```

```
C4  HYDRAULIC CONDUCTIVITIES
229
10.21 4.86E-3
10.26 5.71E-3
10.31 6.26E-3
10.36 5.78E-3
10.41 5.20E-3
10.46 4.41E-3
10.51 4.57E-3
10.56 4.23E-3
10.61 4.95E-3
10.66 2.08E-3
10.71 9.99E-4
10.76 5.67E-4
10.81 5.95E-3
10.86 6.74E-3
10.91 5.94E-3
10.96 6.59E-3
11.01 7.28E-3
11.06 4.82E-3
11.11 8.65E-3
11.16 1.02E-2
11.21 8.03E-3
11.26 8.77E-3
11.31 8.56E-3
11.36 1.01E-2
11.41 1.04E-2
11.46 7.76E-3
11.51 6.63E-3
11.56 6.23E-3
11.61 6.71E-3
11.66 1.25E-4
11.73 6.37E-3
11.78 4.28E-4
11.83 5.20E-5
11.88 1.43E-4
11.93 2.55E-4
11.98 1.09E-4
12.03 1.42E-4
12.08 2.71E-4
12.13 4.14E-4
12.18 7.09E-4
12.23 1.33E-3
12.28 3.53E-3
12.33 2.91E-3
12.38 3.60E-3
12.43 4.02E-3
12.48 4.00E-3
12.53 5.83E-4
12.58 2.57E-4
12.63 2.57E-4
12.68 3.71E-3
12.73 5.05E-3
12.78 3.90E-3
12.83 6.38E-3
12.88 3.38E-3
12.93 4.97E-3
12.98 4.20E-3
13.03 5.81E-3
13.08 6.13E-3
```

```
13.13 6.67E-3
13.18 7.41E-3
13.23 8.22E-3
13.26 4.20E-3
13.31 4.97E-3
13.36 7.98E-3
13.41 7.57E-3
13.46 7.21E-3
13.51 7.09E-3
13.56 6.64E-3
13.61 6.92E-3
13.66 6.02E-3
13.71 5.89E-3
13.76 6.88E-3
13.81 6.25E-3
13.86 5.36E-3
13.91 4.51E-3
13.96 6.85E-3
14.01 8.02E-3
14.06 5.66E-3
14.11 5.62E-3
14.16 5.21E-3
14.21 5.17E-3
14.26 4.79E-3
14.31 3.15E-4
14.36 1.28E-4
14.41 1.14E-4
14.46 8.84E-5
14.51 9.49E-5
14.56 9.64E-5
14.61 1.06E-3
14.66 4.31E-4
14.71 1.39E-4
14.78 9.26E-5
14.83 1.46E-4
14.88 4.32E-4
14.93 1.60E-3
14.98 1.51E-3
15.03 8.53E-4
15.08 6.56E-4
15.13 3.49E-4
15.18 6.80E-4
15.23 1.16E-3
15.28 5.38E-3
15.33 1.08E-2
15.38 9.89E-3
15.43 9.42E-3
15.48 9.96E-3
15.53 6.36E-3
15.58 6.95E-3
15.63 7.43E-3
15.68 7.25E-3
15.73 8.44E-3
15.78 7.16E-3
15.83 9.29E-3
15.88 8.83E-3
15.93 8.41E-3
15.98 1.01E-2
16.03 6.81E-3
16.08 5.74E-3
```

```
16.13 8.18E-5
16.31 3.07E-4
16.36 2.90E-4
16.41 3.19E-4
16.46 2.90E-4
16.51 3.77E-4
16.56 7.47E-4
16.61 1.14E-3
16.66 1.40E-3
16.71 1.32E-3
16.76 1.15E-3
16.81 1.19E-3
16.86 1.31E-3
16.91 1.70E-3
16.96 1.90E-3
17.01 1.95E-3
17.06 1.70E-3
17.11 2.33E-4
17.16 4.18E-4
17.21 5.65E-4
17.26 8.02E-4
17.31 7.92E-4
17.36 4.62E-4
17.41 6.81E-4
17.46 5.67E-4
17.51 2.08E-4
17.56 2.30E-4
17.61 1.31E-4
17.66 5.54E-5
17.71 6.01E-5
17.76 3.88E-5
17.81 1.61E-4
17.83 7.18E-4
17.88 1.49E-4
17.93 1.37E-4
17.98 3.20E-4
18.03 2.90E-4
18.08 2.39E-4
18.13 1.08E-4
18.18 3.70E-5
18.23 2.55E-4
18.28 2.95E-4
18.33 5.62E-4
18.38 3.77E-4
18.43 2.11E-4
18.48 5.06E-4
18.53 9.48E-4
18.58 4.52E-4
18.63 5.04E-4
18.68 8.52E-4
18.73 1.20E-3
18.78 7.61E-4
18.83 7.27E-4
18.88 8.93E-4
18.93 9.32E-4
18.98 1.18E-3
19.03 7.26E-4
19.08 1.33E-3
19.13 1.26E-3
19.18 1.15E-3
```

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19.23 1.42E-3
19.28 1.41E-3
19.35 1.19E-3
19.40 4.77E-4
19.45 3.97E-4
19.50 6.34E-4
19.55 3.90E-4
19.60 8.13E-4
19.65 3.86E-4
19.70 5.86E-4
19.75 2.33E-4
19.80 2.55E-4
19.85 1.76E-4
19.90 1.15E-4
19.95 1.16E-4
20.00 1.44E-4
20.05 1.71E-4
20.10 1.58E-4
20.15 1.26E-4
20.20 6.00E-5
20.25 2.35E-5
20.30 5.42E-5
20.35 6.42E-5
20.73 1.05E-4
20.78 3.81E-5
20.83 7.55E-5
20.88 5.66E-5
20.93 2.71E-4
20.98 1.14E-4
21.03 6.26E-5
21.08 1.14E-4
21.13 3.72E-4
21.18 6.82E-5
21.23 2.65E-5
21.28 4.04E-6
21.33 2.26E-5
21.38 7.93E-4
21.43 1.67E-3
21.48 3.97E-3
21.53 6.07E-3
21.58 3.67E-3
21.63 1.20E-4
21.68 6.08E-5
21.73 4.52E-5
21.78 1.86E-5
21.83 2.63E-4
21.88 7.27E-5
21.93 1.33E-4
21.98 6.36E-5
22.03 6.36E-5
22.08 4.77E-5
```

```
C5  HYDRAULIC CONDUCTIVITIES
164
12.50 1.33E-3
12.55 1.10E-3
12.60 7.51E-4
12.65 3.11E-3
12.70 4.02E-3
12.75 2.04E-3
13.03 9.02E-4
13.08 9.61E-4
13.13 1.64E-3
13.18 2.62E-3
13.23 1.30E-3
13.28 1.07E-3
13.33 3.20E-4
13.38 2.22E-4
13.43 5.09E-4
13.48 6.00E-4
13.53 6.07E-4
13.58 6.86E-4
13.63 4.78E-4
13.68 4.46E-4
13.73 4.47E-4
13.78 3.63E-4
13.83 3.63E-4
13.94 4.01E-3
13.99 7.95E-3
14.04 1.24E-2
14.09 1.23E-2
14.14 5.40E-3
14.19 3.09E-4
14.24 8.66E-5
14.29 1.56E-4
14.34 3.26E-4
14.39 8.40E-4
14.44 5.12E-3
14.63 7.85E-3
14.68 4.76E-3
14.73 5.99E-3
14.78 6.61E-3
14.83 1.26E-2
14.88 2.36E-2
14.93 2.36E-2
14.98 5.77E-3
15.03 4.24E-3
15.24 6.03E-3
15.29 2.54E-3
15.34 4.84E-3
15.39 1.00E-2
15.44 1.08E-2
15.49 5.20E-3
15.60 7.77E-3
15.65 9.55E-3
15.70 6.63E-3
15.75 4.93E-3
15.80 6.20E-3
15.85 4.93E-3
15.90 5.17E-3
15.95 7.42E-3
16.00 7.33E-3
```

```
16.05 5.50E-3
16.10 2.08E-3
16.15 4.25E-5
16.20 3.81E-5
16.25 3.56E-5
16.30 1.63E-4
16.35 3.14E-4
16.40 5.55E-5
16.45 5.55E-5
16.50 8.06E-4
16.55 8.06E-4
16.60 1.17E-3
16.65 1.17E-3
16.70 3.58E-4
16.75 3.29E-4
16.80 1.75E-4
16.85 3.02E-4
16.90 1.62E-4
16.95 1.45E-4
17.13 5.29E-4
17.18 3.98E-4
17.23 4.21E-4
17.28 3.02E-5
17.33 8.04E-5
17.38 2.33E-4
17.46 6.87E-5
17.51 4.46E-4
17.56 6.86E-5
17.61 8.68E-5
17.66 1.03E-4
17.71 1.86E-4
17.76 1.94E-4
17.81 2.61E-4
17.86 1.22E-4
17.91 1.22E-4
17.96 1.12E-4
18.01 1.14E-4
18.06 8.99E-5
18.11 5.77E-5
18.16 8.58E-5
18.21 1.59E-4
18.26 8.17E-5
18.31 4.70E-5
18.36 9.98E-5
18.41 7.12E-5
18.46 6.77E-5
18.51 7.02E-5
18.56 7.28E-5
18.61 5.57E-5
18.66 6.03E-5
18.71 2.27E-5
18.76 1.82E-5
18.81 6.28E-5
18.86 5.23E-4
18.99 3.27E-5
19.04 1.07E-4
19.09 1.07E-4
19.14 6.96E-5
19.19 6.96E-5
19.24 6.51E-5
```

```
19.29 5.50E-5
19.34 1.03E-4
19.39 1.09E-4
19.44 1.20E-4
19.49 1.37E-4
19.54 1.84E-4
19.59 1.12E-4
19.64 1.54E-4
19.69 1.04E-4
19.74 4.88E-5
19.79 4.90E-5
19.84 5.92E-5
19.89 7.18E-5
19.94 6.91E-5
19.99 1.87E-4
20.04 2.32E-4
20.09 1.27E-4
20.14 1.06E-4
20.19 9.25E-5
20.24 1.97E-4
20.29 1.42E-4
20.34 3.08E-5
20.39 3.75E-5
20.44 4.50E-5
20.49 4.50E-5
20.51 2.78E-4
20.56 2.78E-4
20.61 2.58E-3
20.66 2.58E-3
20.71 2.58E-3
20.76 4.95E-4
20.81 4.95E-4
20.86 4.30E-3
20.91 3.81E-3
20.96 3.76E-3
21.01 2.04E-3
21.06 2.04E-3
21.11 8.60E-4
21.16 8.60E-4
21.21 2.44E-3
21.26 2.44E-3
21.31 2.24E-3
21.36 2.24E-3
21.41 3.87E-3
21.46 3.87E-3
21.51 1.34E-4
```

## A.2 Hazen Hydraulic Conductivities.

Hazen hydraulic conductivities (cm/s)
for the depths selected in this study.

The data are arranged by core site.

All depths are in metres.

```
C-1

53
19.51          0.0000810
19.66          0.0027040
19.86          0.0037210
20.21          0.0050410
20.46          0.0400000
20.71          0.0100000
20.96          0.0100000
21.03          0.0026010
21.18          0.0047610
21.28          0.0026010
21.38          0.0000240
21.58          0.0225000
21.73          0.0841000
22.13          0.0361000
22.56          0.0144000
22.76          0.0100000
23.16          0.0032490
23.51          0.0057760
23.61          0.0256000
23.81          0.0100000
24.08          0.0650250
24.33          0.0100000
24.73          0.0225000
24.98          0.0049000
25.23          0.0441000
25.33          0.0361000
25.60          0.0576000
25.75          0.0484000
25.85          0.0324000
26.10          0.0046240
26.30          0.0361000
26.55          0.0324000
26.70          0.0289000
27.13          0.0784000
27.48          0.0529000
27.63          0.0169000
27.83          0.0009000
28.35          0.0000102
28.45          0.0000490
28.65          0.0016000
28.90          0.0225000
29.20          4.0000000
29.45          0.0002890
29.87          0.0100000
30.27          0.0000384
30.62          0.0001210
30.72          0.0010890
30.92          0.0005760
31.07          0.0001440
```

```
31.39          0.0002560
31.79          0.0001440
31.89          0.0000160
32.19          0.0006250


C-2

35
24.08         0.0240250
24.58         0.0306250
25.08         0.0000160
25.48         0.0007563
25.60         0.0008410
25.75         0.0100000
25.80         0.0002890
26.05         0.0025000
26.25         0.0012250
26.50         0.0034810
26.75         0.0020250
27.00         0.0002560
27.13         0.0025000
27.58         0.0004000
27.78         0.0006250
28.03         0.0028090
28.43         0.0000810
28.65         0.0024010
28.75         0.0005290
29.30         0.0000563
29.35         0.0030250
30.18         0.0002890
30.28         0.0026010
30.68         0.0000593
30.78         0.0029160
31.23         0.0047610
31.43         5.2900000
31.70         0.0027040
32.35         0.0342250
32.60         0.0484000
32.85         0.0049000
32.95         0.0900000
33.22         4.8400000
33.32         0.1225000
33.52         0.0900000


C-3

32
22.40      0.0068890
22.60      0.0050410
23.00      0.0046240
23.15      0.0036000
23.60      0.0046240
23.93      0.0047610
24.28      0.0054760
24.43      0.0049000
24.48      0.0050410
25.18      0.0050410
25.45      0.0121000
```

```
25.95       0.0044890
26.55       0.0036000
26.75       0.0072250
26.97       0.0027040
27.07       0.0060840
27.32       0.0027040
27.67       0.0000640
27.92       0.0002723
28.50       0.0002890
28.85       0.0006760
29.25       0.0011560
29.70       0.0000372
29.85       0.0003610
30.02       0.0001690
30.22       0.0001000
30.40       0.0000490
30.70       0.0006250
30.95       0.0000176
31.25       0.0036000
31.65       0.0036000
31.70       0.0028622


C-4

45
10.21       0.0043560
10.31       0.0064000
10.76       0.0006760
10.86       0.0049000
11.16       0.0079210
11.41       0.0081000
11.66       0.0002560
11.73       0.0056250
11.83       0.0001440
12.48       0.0036000
12.58       0.0002890
12.83       0.0056250
13.23       0.0086490
13.26       0.0049000
13.36       0.0034810
14.01       0.0079210
14.26       0.0073960
14.46       0.0000360
14.71       0.0001960
14.78       0.0001690
14.93       0.0009610
15.13       0.0005760
15.33       0.0064000
15.63       0.0049000
16.08       0.0026010
16.13       0.0000090
16.31       0.0004000
17.01       0.0023040
17.11       0.0005760
17.26       0.0012960
17.76       0.0000490
17.81       0.0003240
17.83       0.0000230
18.18       0.0000202
```

```
18.73       0.0016810
19.28       0.0024010
19.35       0.0016000
19.70       0.0009000
19.95       0.0001000
20.35       0.0000640
20.73       0.0000410
21.28       0.0000017
21.53       0.0049000
21.78       0.0000160
22.08       0.0000073


C-5


39
12.50           0.0024010
12.70           0.0031360
12.75           0.0029160
13.03           0.0022090
13.18           0.0025000
13.38           0.0004000
13.78           0.0004000
13.94           0.0100000
14.09           0.0110250
14.24           0.0001690
14.44           0.0040960
14.63           0.0090250
14.93           0.0156250
15.03           0.0064000
15.24           0.0062410
15.44           0.0057760
15.49           0.0047610
15.60           0.0064000
15.65           0.0072250
15.95           0.0049000
16.65           0.0025000
17.13           0.0011560
17.28           0.0000723
17.38           0.0006250
17.46           0.0002890
17.51           0.0012250
17.81           0.0004000
18.21           0.0001960
18.76           0.0000360
18.86           0.0023040
18.99           0.0003610
19.54           0.0005062
19.74           0.0004410
20.04           0.0009923
20.44           0.0002250
20.51           0.0007840
20.86           0.0256000
21.51           0.0023040
```

## A.3 Correlated Hazen and Permeameter Hydraulic Conductivities.

Correlated Hazen and Permeameter Hydraulic Conductivities in cm/s used in the comparison profile: figure 7.

NUMBER OF VALUES = 203

| HAZEN | PERMEAMETER |
|---|---|
| 0.0000810 | 2.74E-4 |
| 0.0027040 | 2.09E-3 |
| 0.0037210 | 4.11E-3 |
| 0.0050410 | 6.69E-3 |
| 0.0400000 | 9.34E-3 |
| 0.0100000 | 7.62E-3 |
| 0.0100000 | 9.27E-3 |
| 0.0026010 | 1.43E-3 |
| 0.0047610 | 2.78E-3 |
| 0.0026010 | 1.81E-3 |
| 0.0000240 | 2.25E-4 |
| 0.0225000 | 1.29E-2 |
| 0.0841000 | 3.73E-2 |
| 0.0361000 | 1.70E-2 |
| 0.0144000 | 1.27E-2 |
| 0.0100000 | 5.99E-3 |
| 0.0032490 | 2.55E-2 |
| 0.0057760 | 4.04E-3 |
| 0.0256000 | 8.29E-2 |
| 0.0100000 | 2.53E-3 |
| 0.0650250 | 2.40E-2 |
| 0.0100000 | 7.30E-3 |
| 0.0225000 | 9.92E-3 |
| 0.0049000 | 1.87E-2 |
| 0.0441000 | 1.40E-3 |
| 0.0361000 | 1.20E-2 |
| 0.0576000 | 2.57E-2 |
| 0.0484000 | 3.26E-2 |
| 0.0324000 | 8.06E-3 |
| 0.0046240 | 1.66E-3 |
| 0.0361000 | 2.29E-2 |
| 0.0324000 | 1.48E-2 |
| 0.0289000 | 6.49E-3 |
| 0.0784000 | 4.59E-2 |
| 0.0529000 | 2.67E-2 |
| 0.0169000 | 1.39E-2 |
| 0.0009000 | 3.20E-3 |
| 0.0000102 | 2.90E-2 |
| 0.0000490 | 4.45E-5 |
| 0.0016000 | 1.35E-4 |
| 0.0225000 | 1.28E-2 |
| 4.0000000 | 2.44E-2 |
| 0.0002890 | 1.11E-4 |
| 0.0100000 | 6.26E-3 |
| 0.0000384 | 2.85E-5 |
| 0.0001210 | 1.73E-4 |
| 0.0010890 | 4.36E-3 |
| 0.0005760 | 3.08E-4 |
| 0.0001440 | 9.26E-5 |
| 0.0002560 | 3.07E-5 |

```
0.0001440 3.99E-4
0.0000160 1.05E-5
0.0006250 4.54E-4
0.0240250  1.57E-2
0.0306250 1.37E-2
0.0000160 2.77E-5
0.0007563 2.18E-4
0.0008410 3.09E-4
0.0100000 7.71E-3
0.0002890 1.27E-4
0.0025000 9.99E-4
0.0012250 6.18E-4
0.0034810 2.34E-3
0.0020250 1.30E-3
0.0002560 3.29E-4
0.0025000 9.37E-5
0.0004000 1.87E-3
0.0006250 7.85E-5
0.0028090 9.36E-3
0.0000810 1.34E-4
0.0024010 8.14E-5
0.0005290 3.26E-4
0.0000563 7.73E-5
0.0030250 5.67E-3
0.0002890 1.31E-4
0.0026010 1.35E-3
0.0000593 5.39E-5
0.0029160 2.10E-3
0.0047610 3.98E-3
5.2900000 3.59E-3
0.0027040 2.51E-4
0.0342250 6.10E-3
0.0484000 2.00E-3
0.0049000 2.51E-3
0.0900000 8.40E-4
4.8400000 3.62E-2
0.1225000 5.23E-2
0.0900000 3.41E-2
0.0068890 6.39E-3
0.0050410 3.52E-3
0.0046240 1.45E-2
0.0036000 2.30E-5
0.0046240 6.62E-3
0.0047610 5.01E-3
0.0054760 6.38E-3
0.0049000 5.04E-3
0.0050410 6.88E-3
0.0050410 5.34E-3
0.0121000 7.57E-3
0.0044890 9.08E-3
0.0036000 5.06E-3
0.0072250 5.20E-3
0.0027040 1.24E-3
0.0060840 5.83E-3
0.0027040 9.08E-4
0.0000640 9.88E-5
0.0002723 2.86E-4
0.0002890 1.32E-4
0.0006760 3.78E-4
0.0011560 6.92E-4
```

```
0.0000372 2.83E-5
0.0003610 2.54E-4
0.0001690 2.01E-4
0.0001000 1.18E-4
0.0000490 8.18E-5
0.0006250 2.24E-3
0.0000176 6.30E-5
0.0036000 3.14E-3
0.0036000 9.14E-3
0.0028622 1.98E-3
0.0043560 4.86E-3
0.0064000 6.26E-3
0.0006760 5.67E-4
0.0049000 6.74E-3
0.0079210 1.02E-2
0.0081000 1.04E-2
0.0002560 1.25E-4
0.0056250 6.37E-3
0.0001440 5.20E-5
0.0036000 4.00E-3
0.0002890 2.57E-4
0.0056250 6.38E-3
0.0086490 8.22E-3
0.0049000 4.20E-3
0.0034810 7.98E-3
0.0079210 8.02E-3
0.0073960 4.79E-3
0.0000360 8.84E-5
0.0001960 1.39E-4
0.0001690 9.26E-5
0.0009610 1.60E-3
0.0005760 3.49E-4
0.0064000 1.08E-2
0.0049000 7.43E-3
0.0026010 5.74E-3
0.0000090 8.18E-5
0.0004000 3.07E-4
0.0023040 1.95E-3
0.0005760 2.33E-4
0.0012960 8.02E-4
0.0000490 3.88E-5
0.0003240 1.61E-4
0.0000230 7.18E-4
0.0000202 3.70E-5
0.0016810 1.20E-3
0.0024010 1.41E-3
0.0016000 1.19E-3
0.0009000 5.86E-4
0.0001000 1.16E-4
0.0000640 6.42E-5
0.0000410 1.05E-4
0.0000017 4.04E-6
0.0049000 6.07E-3
0.0000160 1.86E-5
0.0000073 4.77E-5
0.0024010 1.33E-3
0.0031360 4.02E-3
0.0029160 2.04E-3
0.0022090 9.02E-4
0.0025000 2.62E-3
```

```
0.0004000 2.22E-4
0.0004000 3.63E-4
0.0100000 4.01E-3
0.0110250 1.23E-2
0.0001690 8.66E-5
0.0040960 5.12E-3
0.0090250 7.85E-3
0.0156250 2.36E-2
0.0064000 4.24E-3
0.0062410 6.03E-3
0.0057760 1.08E-2
0.0047610 5.20E-3
0.0064000 7.77E-3
0.0072250 9.55E-3
0.0049000 7.42E-3
0.0025000 1.17E-3
0.0011560 5.29E-4
0.0000723 3.02E-5
0.0006250 2.33E-4
0.0002890 6.87E-5
0.0012250 4.46E-4
0.0004000 2.61E-4
0.0001960 1.59E-4
0.0000360 1.82E-5
0.0023040 5.23E-4
0.0003610 3.27E-5
0.0005062 1.84E-4
0.0004410 4.88E-5
0.0009923 2.32E-4
0.0002250 4.50E-5
0.0007840 2.78E-4
0.0256000 4.30E-3
0.0023040 1.34E-4
```

## A.4 Correlated and Averaged Permeameter Hydraulic Conductivities.

Permeameter hydraulic conductivities from the 5 cm tests that have been correlated and averaged with the 20 cm packer-slug tests. All values are in cm/s. Depths are in metres. The data are presented by core site.

C-1

| | |
|---|---|
| 31.95 | 2.61E-5 |
| 31.75 | 1.42E-4 |
| 31.55 | 4.57E-5 |
| 31.15 | 2.03E-4 |
| 30.95 | 1.80E-4 |
| 30.75 | 6.52E-4 |
| 30.55 | 1.30E-3 |
| 30.35 | 3.86E-5 |
| 30.15 | 4.08E-5 |
| 29.95 | 7.46E-5 |
| 29.55 | 1.48E-4 |
| 29.35 | 2.32E-3 |
| 29.15 | 1.66E-2 |
| 28.95 | 1.10E-2 |
| 28.75 | 8.59E-3 |
| 28.55 | 9.85E-4 |
| 28.35 | 1.30E-2 |
| 27.75 | 7.99E-3 |
| 27.55 | 1.90E-2 |
| 27.35 | 2.12E-2 |
| 27.15 | 3.34E-2 |
| 26.75 | 1.44E-2 |
| 26.55 | 1.05E-2 |
| 26.35 | 8.70E-3 |
| 26.15 | 1.10E-2 |
| 25.95 | 6.42E-2 |
| 25.75 | 1.76E-2 |
| 25.15 | 9.50E-3 |
| 24.95 | 1.83E-2 |
| 24.75 | 1.44E-2 |
| 24.55 | 1.56E-2 |
| 24.35 | 1.21E-2 |
| 24.15 | 1.98E-2 |
| 23.75 | 1.08E-2 |
| 23.55 | 3.09E-2 |
| 23.35 | 7.81E-3 |
| 23.15 | 1.68E-2 |
| 22.95 | 1.17E-2 |
| 22.75 | 1.24E-2 |
| 22.55 | 1.86E-2 |
| 22.15 | 1.84E-2 |
| 21.95 | 2.84E-2 |
| 21.75 | 4.40E-2 |
| 21.55 | 1.60E-2 |
| 21.35 | 4.99E-3 |
| 21.15 | 2.24E-3 |
| 20.75 | 9.48E-3 |
| 20.55 | 8.76E-3 |
| 20.35 | 7.27E-3 |

```
20.15 5.61E-3
```

C-2

```
33.23 4.64E-2
32.83 2.19E-3
32.63 4.24E-3
32.43 2.80E-3
32.23 6.79E-3
32.03 1.63E-3
31.83 1.17E-4
31.03 1.45E-3
30.83 1.76E-3
30.63 6.60E-4
30.43 3.36E-4
30.23 9.47E-4
29.23 2.74E-3
29.03 1.57E-4
28.83 1.18E-4
28.63 1.73E-4
28.23 4.35E-3
28.03 7.30E-3
27.83 3.76E-3
27.63 2.55E-4
27.43 9.60E-4
27.23 9.82E-5
26.83 3.09E-4
26.63 9.43E-4
26.43 1.44E-3
26.23 1.01E-3
26.03 5.40E-4
25.83 5.22E-4
25.63 3.62E-3
25.23 1.74E-4
25.03 4.44E-5
24.83 9.74E-3
24.63 1.74E-2
24.43 2.45E-2
24.23 2.12E-2
```

C-3

```
31.31 3.66E-3
31.11 1.25E-3
30.91 1.47E-4
30.71 1.05E-3
30.51 5.14E-4
30.11 1.39E-4
29.71 2.03E-4
29.51 7.14E-5
29.31 4.07E-4
29.11 4.85E-4
28.91 3.68E-4
28.71 3.01E-4
28.51 1.58E-4
27.71 3.23E-4
27.51 1.14E-3
27.31 1.73E-3
```

| | |
|---|---|
| 27.11 | 3.47E-3 |
| 26.51 | 5.37E-3 |
| 26.31 | 6.00E-3 |
| 26.11 | 7.90E-3 |
| 25.91 | 8.52E-3 |
| 25.71 | 7.95E-3 |
| 25.51 | 8.31E-3 |
| 24.91 | 5.54E-3 |
| 24.71 | 5.84E-3 |
| 24.51 | 6.04E-3 |

C-4

| | |
|---|---|
| 10.29 | 5.41E-3 |
| 10.49 | 3.96E-3 |
| 10.69 | 3.56E-3 |
| 10.89 | 6.16E-3 |
| 11.09 | 8.91E-3 |
| 11.29 | 9.20E-3 |
| 11.49 | 4.92E-3 |
| 11.69 | 1.75E-3 |
| 11.89 | 1.94E-4 |
| 12.09 | 1.496E-3 |
| 12.29 | 3.63E-3 |
| 12.49 | 1.202E-3 |
| 12.69 | 4.68E-3 |
| 12.89 | 5.28E-3 |
| 13.09 | 2.65E-3 |
| 13.29 | 2.77E-3 |
| 13.49 | 2.67E-3 |
| 13.69 | 2.44E-3 |
| 13.89 | 6.26E-3 |
| 14.09 | 5.20E-3 |
| 14.29 | 1.61E-4 |
| 14.49 | 4.21E-4 |
| 14.69 | 2.02E-4 |
| 14.89 | 1.16E-3 |
| 15.09 | 1.89E-3 |
| 15.29 | 1.00E-2 |
| 15.49 | 7.00E-3 |
| 15.69 | 8.43E-3 |
| 15.89 | 7.76E-3 |
| 16.29 | 3.02E-4 |
| 16.49 | 9.16E-4 |
| 16.69 | 1.24E-3 |
| 16.89 | 7.25E-3 |
| 17.09 | 5.04E-4 |
| 17.29 | 6.26E-4 |
| 17.49 | 1.56E-4 |
| 17.69 | 2.44E-4 |
| 17.89 | 2.24E-4 |
| 18.09 | 1.60E-4 |
| 18.29 | 3.61E-4 |
| 18.49 | 6.02E-4 |
| 18.69 | 8.85E-4 |
| 18.89 | 9.33E-4 |
| 19.09 | 1.29E-3 |
| 19.29 | 8.69E-4 |

```
19.49 5.56E-4
19.69 3.12E-4
```

C-5

```
12.52 1.57E-3
13.12 1.66E-3
13.32 4.13E-4
13.52 5.54E-4
13.72 3.91E-4
13.92 9.16E-3
14.12 1.49E-3
14.32 2.10E-3
14.72 1.22E-2
14.92 1.12E-2
15.32 7.71E-3
15.72 5.67E-3
15.92 6.36E-3
16.12 5.49E-4
16.32 1.47E-4
16.52 9.88E-4
16.72 2.91E-4
17.12 3.44E-4
17.52 1.76E-4
17.72 1.91E-4
17.92 1.10E-4
18.12 9.60E-5
18.32 7.14E-5
18.52 6.48E-5
18.72 1.57E-4
19.12 7.78E-5
19.32 9.68E-5
19.52 1.47E-4
19.72 6.52E-5
19.92 1.40E-4
20.12 1.31E-4
20.32 6.38E-5
20.52 1.43E-3
20.72 1.97E-3
20.92 2.91E-3
21.12 1.65E-3
21.32 3.06E-3
```

## A.5 Packer-Slug Test Values.

The following data are the pack-slug test hydraulic conductivities for each hole and each installation factor (F/A). Hydraulic conductivities are in cm/s, depths are in metres.

F/A = 6.54

T-1

| | |
|---|---|
| 32.75 | 5.82033E-03 |
| 32.55 | 4.69024E-03 |
| 32.35 | 4.39842E-03 |
| 32.15 | 4.5199E-03 |
| 31.95 | 4.73689E-03 |
| 31.75 | 5.51517E-03 |
| 31.55 | 4.57067E-03 |
| 31.35 | 5.05002E-03 |
| 31.15 | 4.32716E-03 |
| 30.95 | 2.40053E-03 |
| 30.75 | 2.74304E-03 |
| 30.55 | 2.70852E-03 |
| 30.35 | 4.43019E-03 |
| 30.15 | 4.36558E-03 |
| 29.95 | 3.86071E-03 |
| 29.75 | 4.33531E-03 |
| 29.55 | 4.01943E-03 |
| 29.35 | 3.42966E-03 |
| 29.15 | 3.35434E-03 |
| 28.95 | 5.05651E-03 |
| 28.75 | 3.31402E-03 |
| 28.55 | 4.38128E-03 |
| 28.35 | 5.4596E-03 |
| 28.15 | 6.41948E-03 |
| 27.95 | 8.52243E-03 |
| 27.75 | 4.07976E-03 |
| 27.55 | 4.49168E-03 |
| 27.35 | 4.13202E-03 |
| 27.15 | 4.77012E-03 |
| 26.95 | 6.4805E-03 |
| 26.75 | 3.99151E-03 |
| 26.55 | 4.31248E-03 |
| 26.35 | 1.47868E-02 |
| 26.15 | 1.18488E-02 |
| 25.95 | 1.15924E-02 |
| 25.75 | 1.08766E-02 |
| 25.55 | 8.2049E-03 |
| 25.35 | 9.98894E-03 |
| 25.15 | .01003 |
| 24.95 | 9.8926E-03 |
| 24.75 | 1.00034E-02 |
| 24.55 | 4.01556E-03 |
| 24.35 | 1.13171E-02 |
| 24.15 | 7.84674E-03 |
| 23.95 | 7.70925E-03 |
| 23.75 | 7.95397E-03 |
| 23.55 | 6.70619E-03 |
| 23.35 | 8.67573E-03 |
| 23.15 | 8.24136E-03 |

```
    22.95                8.62558E-03
    22.75                7.78132E-03
    22.55                7.55548E-03
    22.35                8.40029E-03
    22.15                7.13389E-03
    21.95                7.87363E-03
    21.75                6.63781E-03
    21.55                9.10683E-03
    21.35                9.70658E-03
    21.15                .009285
    20.95                6.51899E-03
    20.75                7.05269E-03
    20.55                7.32661E-03
    20.35                4.1222E-03
    20.15                4.33269E-03


   T-2


    33.23                3.61725E-04
    33.03                1.49691E-03
    32.8299                3.89755E-03
    32.6299                4.04853E-03
    32.43                5.57557E-03
    32.23                6.9341E-03
    32.03                .012436
    31.8299                1.52339E-02
    31.63                4.45618E-02
   31.03                1.10006E-02
    30.8299                4.71542E-03
    30.63                2.67259E-03
    30.4299                1.43627E-03
    30.23                1.1345E-03
    30.03                9.49329E-04
    29.8299                8.90494E-04
    29.63                8.34911E-04
    29.4299                7.32329E-04
    29.23                6.31892E-04
    29.03                7.76457E-04
    28.8299                7.73864E-04
    28.63                7.93837E-04
    28.4299                6.60603E-04
    28.23                5.87451E-04
    28.03                7.76804E-04
    27.8299                8.37975E-04
    27.63                7.9323E-04
    27.4299                1.12431E-03
    27.23                1.99838E-03
    27.03                1.76286E-03
    26.8299                2.11438E-03
    26.63                2.12473E-03
    26.4299                2.07877E-03
    26.23                2.22655E-03
    26.0299                2.07761E-03
    25.8299                2.12211E-03
    25.6299                3.14855E-03
    25.43                4.23614E-03
    25.23                5.21326E-03
    25.03                5.38224E-03
```

| | |
|---|---|
| 24.83 | 5.1629E-03 |
| 24.63 | 6.00329E-03 |
| 24.43 | 3.96599E-03 |
| 24.23 | 3.01814E-03 |
| 24.03 | 2.68813E-03 |
| 23.83 | 3.34226E-03 |
| 23.63 | 4.13433E-03 |

T-3

| | |
|---|---|
| 31.31 | 4.66093E-03 |
| 31.11 | 6.26933E-03 |
| 30.91 | 7.98105E-03 |
| 30.71 | 8.9046E-03 |
| 30.51 | 7.01513E-03 |
| 30.31 | 5.65676E-03 |
| 30.11 | 4.8478E-03 |
| 29.91 | 4.41817E-03 |
| 29.71 | 5.04691E-03 |
| 29.51 | 2.60364E-03 |
| 29.31 | 2.48792E-03 |
| 29.11 | 1.44621E-03 |
| 28.91 | 2.24939E-03 |
| 28.71 | 1.75329E-03 |
| 28.51 | 3.01426E-03 |
| 28.31 | 2.14238E-03 |
| 28.11 | 2.3652E-03 |
| 27.91 | 2.63841E-03 |
| 27.71 | 2.21221E-03 |
| 27.51 | 3.94447E-03 |
| 27.31 | 3.69955E-03 |
| 27.11 | 3.44486E-03 |
| 26.91 | 5.31494E-03 |
| 26.71 | 7.80602E-03 |
| 26.51 | 8.99351E-03 |
| 26.31 | 8.36304E-03 |
| 26.11 | 6.09759E-03 |
| 25.91 | 6.24842E-03 |
| 25.71 | 7.25174E-03 |
| 25.51 | 8.77462E-03 |
| 25.31 | 7.64984E-03 |
| 25.11 | 7.89033E-03 |
| 24.91 | 7.47063E-03 |
| 24.71 | 6.43138E-03 |
| 24.51 | 4.66595E-03 |

T-4

| | |
|---|---|
| 19.6899 | 1.43922E-03 |
| 19.49 | 1.41566E-03 |
| 19.2899 | 3.63934E-04 |
| 19.09 | 1.76808E-03 |
| 18.89 | 2.34547E-03 |

```
18.6899              8.35344E-04
18.49               1.46602E-03
18.2899              1.67222E-03
18.09               1.1582E-03
17.89               3.03057E-03
17.6899              3.3505E-03
17.49               2.11324E-03
17.2899              1.24297E-03
17.09               1.73799E-03
16.89               2.60489E-03
16.6899              3.78269E-03
16.49               3.43227E-03
16.2899              4.98416E-03
16.09               2.58706E-03
15.89               4.99777E-03
15.69               1.77193E-03
15.49               1.76857E-03
15.2899              2.67623E-03
15.0899              2.95069E-03
14.89               4.3278E-03
14.69               4.65795E-03
14.49               5.08171E-03
14.2899              1.29084E-03
14.0899              8.5582E-03
13.89               3.67371E-03
13.69               4.20568E-03
13.49               2.95142E-03
13.2899              1.43895E-03
13.0899              3.19174E-03
12.8899              2.69678E-03
12.69               .00299
12.49               2.44109E-03
12.29               3.32591E-03
12.09               3.86726E-03
11.89               5.43072E-03
11.69               4.94763E-03
11.49               5.78962E-03
11.29               8.85671E-03
11.09               8.05735E-03
10.89               5.7822E-03
10.69               4.93834E-03
10.49               6.79892E-03
10.29               7.62078E-03
10.09               5.10112E-03
```

T-5

```
21.32               1.65833E-03
21.1199              2.64572E-03
20.92               2.74451E-03
20.72               2.98561E-03
20.52               3.13219E-03
20.32               1.76195E-03
20.1199              3.14116E-03
19.92               2.46034E-03
19.72               1.82852E-03
19.52               1.1927E-03
```

```
19.32                    1.59833E-03
19.1199                    1.35306E-03
18.92                    1.90971E-03
18.72                    1.83945E-03
18.52                    3.08937E-03
18.32                    1.68976E-03
18.1199                    1.96199E-03
17.92                    1.64809E-03
17.72                    1.8475E-03
17.52                    1.49945E-03
17.32                    1.64354E-03
17.1199                    2.10116E-03
16.92                    1.35476E-03
16.72                    1.62559E-03
16.52                    1.69059E-03
16.32                    2.60778E-03
16.1199                    2.39204E-03
15.92                    2.04005E-03
15.72                    1.95548E-03
15.52                    1.69932E-03
15.32                    1.32448E-03
15.12                    1.34735E-03
14.92                    1.5655E-03
14.72                    1.15899E-03
14.52                    1.14711E-03
14.32                    1.98135E-03
14.12                    1.96345E-03
13.92                    1.90242E-03
13.72                    1.31223E-03
13.52                    1.42061E-03
13.32                    1.87442E-03
13.12                    2.8339E-03
12.92                    1.70668E-03
12.7199                    .002141
12.5199                    1.72475E-03
12.32                    2.07106E-03
12.12                    2.01085E-03
11.92                    1.32835E-03
11.7199                    1.19086E-03
11.5199                    1.78544E-03
11.32                    2.13746E-03
11.12                    1.16288E-03


F/A = 7.07


T-1


 32.75                   5.38401E-03
 32.55                   4.33864E-03
 32.35                   4.06869E-03
 32.15                   4.18107E-03
 31.95                   4.38179E-03
 31.75                   5.10172E-03
 31.55                   4.22803E-03
 31.35                   4.67145E-03
```

| | |
|---|---|
| 31.15 | 4.00278E-03 |
| 31.15 | 2.79579E-03 |
| 30.95 | 2.22057E-03 |
| 30.75 | 2.53741E-03 |
| 30.55 | 2.50547E-03 |
| 30.35 | 4.09808E-03 |
| 30.15 | 4.03831E-03 |
| 29.95 | 3.57129E-03 |
| 29.75 | 4.01032E-03 |
| 29.55 | 3.71811E-03 |
| 29.35 | 3.17256E-03 |
| 29.15 | 3.10288E-03 |
| 28.95 | 4.67745E-03 |
| 28.75 | 3.06558E-03 |
| 28.55 | 4.05284E-03 |
| 28.35 | 5.05033E-03 |
| 28.15 | 5.93824E-03 |
| 27.95 | 7.88355E-03 |
| 27.75 | 3.77392E-03 |
| 27.55 | 4.15497E-03 |
| 27.35 | 3.82227E-03 |
| 27.15 | 4.41253E-03 |
| 26.95 | 5.99469E-03 |
| 26.75 | 3.69229E-03 |
| 26.55 | 3.98919E-03 |
| 26.35 | 1.36783E-02 |
| 26.15 | 1.09606E-02 |
| 25.95 | 1.07233E-02 |
| 25.75 | 1.00612E-02 |
| 25.55 | 7.58982E-03 |
| 25.35 | 9.24012E-03 |
| 25.15 | 9.27811E-03 |
| 24.95 | .009151 |
| 24.75 | 9.25358E-03 |
| 24.55 | 3.71454E-03 |
| 24.35 | 1.04687E-02 |
| 24.15 | 7.25852E-03 |
| 23.95 | 7.13132E-03 |
| 23.75 | 7.3577E-03 |
| 23.55 | 6.20346E-03 |
| 23.35 | 8.02536E-03 |
| 23.15 | 7.62355E-03 |
| 22.95 | 7.97897E-03 |
| 22.75 | 7.19799E-03 |
| 22.55 | 6.98909E-03 |
| 22.35 | 7.77056E-03 |
| 22.15 | 6.5991E-03 |
| 21.95 | 7.28338E-03 |
| 21.75 | 6.14021E-03 |
| 21.55 | 8.42414E-03 |
| 21.35 | 8.97893E-03 |
| 21.15 | 8.58896E-03 |
| 20.95 | 6.0303E-03 |
| 20.75 | 6.52399E-03 |
| 20.55 | 6.77738E-03 |
| 20.35 | 3.81318E-03 |

```
 33.23                3.34609E-04
 33.03                1.38469E-03
 32.8299                3.60537E-03
 32.6299                3.74503E-03
 32.43                5.1576E-03
 32.23                6.41429E-03
 32.03                1.15037E-02
 31.8299                1.40919E-02
 31.63                4.12213E-02
 31.03                .010176
 30.8299                4.36193E-03
 30.63                2.47224E-03
 30.4299                1.3286E-03
 30.23                1.04945E-03
 30.03                8.78163E-04
 29.8299                8.23738E-04
 29.63                7.72322E-04
 29.4299                6.7743E-04
 29.23                5.84522E-04
 29.03                7.1825E-04
 28.8299                7.15852E-04
 28.63                7.34327E-04
 28.4299                6.11081E-04
 28.23                5.43413E-04
 28.03                7.18571E-04
 27.8299                7.75156E-04
 27.63                7.33766E-04
 27.4299                1.04003E-03
 27.23                1.84857E-03
 27.03                1.6307E-03
 26.8299                1.95587E-03
 26.63                1.96545E-03
 26.4299                1.92294E-03
 26.23                2.05963E-03
 26.0299                1.92186E-03
 25.8299                1.96303E-03
 25.6299                2.91252E-03
 25.43                3.91858E-03
 25.23                4.82245E-03
 25.03                4.97876E-03
 24.83                4.77586E-03
 24.63                5.55326E-03
 24.43                3.66868E-03
 24.23                2.79188E-03
 24.03                2.48662E-03
 23.83                3.0917E-03
 23.63                3.8244E-03


T-3


 31.31                4.31153E-03
 31.11                5.79935E-03
 30.91                7.38276E-03
 30.71                8.23707E-03
 30.51                6.48925E-03
```

```
    30.31                  5.23271E-03
    30.11                  4.48439E-03
    29.91                  4.08696E-03
    29.71                  4.66857E-03
    29.51                  2.40846E-03
    29.31                  2.30141E-03
    29.11                  1.33779E-03
    28.91                  2.08076E-03
    28.71                  1.62186E-03
    28.51                  2.7883E-03
    28.31                  1.98178E-03
    28.11                  2.18789E-03
    27.91                  2.44062E-03
    27.71                  2.04638E-03
    27.51                  3.64878E-03
    27.31                  3.42221E-03
    27.11                  3.18662E-03
    26.91                  4.91651E-03
    26.71                  7.22084E-03
    26.51                  8.31932E-03
    26.31                  7.73611E-03
    26.11                  5.64049E-03
    25.91                  5.78001E-03
    25.71                  6.70812E-03
    25.51                  8.11683E-03
    25.31                  7.07637E-03
    25.11                  7.29884E-03
    24.91                  6.9106E-03
    24.71                  5.94926E-03
    24.51                  4.31617E-03


  T-4


    19.6899                  1.33133E-03
    19.49                  1.30954E-03
    19.2899                  3.36652E-04
    19.09                  1.63554E-03
    18.89                  2.16964E-03
    18.6899                  7.72722E-04
    18.49                  1.35612E-03
    18.2899                  1.54686E-03
    18.09                  1.07138E-03
    17.89                  2.80339E-03
    17.6899                  3.09933E-03
    17.49                  1.95482E-03
    17.2899                  1.14979E-03
    17.09                  1.6077E-03
    16.89                  2.40962E-03
    16.6899                  3.49913E-03
    16.49                  3.17497E-03
    16.2899                  4.61052E-03
    16.09                  2.39312E-03
    15.89                  4.62312E-03
    15.69                  1.63909E-03
    15.49                  1.63599E-03
    15.2899                  2.47561E-03
    15.0899                  2.72949E-03
```

```
 14.89                  4.00336E-03
 14.69                  4.30877E-03
 14.49                  4.70077E-03
 14.2899                  1.19407E-03
 14.0899                  7.91664E-03
 13.89                  3.39831E-03
 13.69                  3.8904E-03
 13.49                  2.73017E-03
 13.2899                  1.33108E-03
 13.0899                  2.95247E-03
 12.8899                  2.49462E-03
 12.69                  2.76586E-03
 12.49                  2.25809E-03
 12.29                  3.07658E-03
 12.09                  3.57735E-03
 11.89                  5.02361E-03
 11.69                  4.57673E-03
 11.49                  5.3556E-03
 11.29                  8.19277E-03
 11.09                  7.45333E-03
 10.89                  5.34874E-03
 10.69                  4.56814E-03
 10.49                  6.28924E-03
 10.29                  7.04949E-03
 10.09                  4.71872E-03


T-5


21.32                  1.53401E-03
 21.1199                  2.44739E-03
 20.92                  2.53877E-03
 20.72                  2.76179E-03
 20.52                  2.89739E-03
 20.32                  1.62986E-03
 20.1199                  2.90568E-03
 19.92                  2.2759E-03
 19.72                  1.69144E-03
 19.52                  1.10329E-03
 19.32                  1.47851E-03
 19.1199                  1.25163E-03
 18.92                  1.76655E-03
 18.72                  1.70156E-03
 18.52                  2.85777E-03
 18.32                  1.56309E-03
 18.1199                  1.81491E-03
 17.92                  1.52455E-03
 17.72                  .001709
 17.52                  1.38704E-03
 17.32                  1.52033E-03
 17.1199                  1.94365E-03
 16.92                  1.2532E-03
 16.72                  1.50372E-03
 16.52                  1.56385E-03
 16.32                  2.41229E-03
 16.1199                  2.21272E-03
 15.92                  1.88712E-03
 15.72                  1.80889E-03
 15.52                1.57193E-03
 15.32                1.22519E-03
 15.12                1.24634E-03
 14.92                1.44814E-03
 14.72                1.0721E-03
 14.52                1.06112E-03
 14.32                1.83282E-03
 14.12                1.81626E-03
 13.92                1.7598E-03
 13.72                1.21386E-03
 13.52                1.31411E-03
 13.32                1.7339E-03
 13.12                2.62145E-03
 12.92                1.57874E-03
 12.7199                1.9805E-03
 12.5199                1.59545E-03
 12.32                1.9158E-03
 12.12                1.86011E-03
 11.92                1.22877E-03
 11.7199                1.10159E-03
 11.5199                1.6516E-03
 11.32                1.97723E-03
 11.12                1.0757E-03


F/A = 14.18


T-1


32.75                2.68441E-03
 32.55                2.1632E-03
 32.35                2.0286E-03
 32.15                2.08463E-03
 31.95                2.18471E-03
 31.75                2.54366E-03
 31.55                2.10805E-03
 31.35                2.32913E-03
 31.15                1.99574E-03
 30.95                1.10715E-03
 30.75                1.26512E-03
 30.55                1.2492E-03
 30.35                2.04326E-03
 30.15                2.01346E-03
 29.95                1.78061E-03
 29.75                1.9995E-03
 29.55                1.85381E-03
 29.35                1.5818E-03
 29.15                1.54706E-03
 28.95                2.33213E-03
 28.75                1.52846E-03
 28.55                2.0207E-03
 28.35                2.51804E-03
 28.15                2.96074E-03
 27.95                3.93065E-03
 27.75                1.88164E-03
```

| | |
|---|---|
| 27.55 | 2.07162E-03 |
| 27.35 | 1.90574E-03 |
| 27.15 | 2.20004E-03 |
| 26.95 | 2.98889E-03 |
| 26.75 | 1.84093E-03 |
| 26.55 | 1.98897E-03 |
| 26.35 | 6.81988E-03 |
| 26.15 | 5.46485E-03 |
| 25.95 | 5.34656E-03 |
| 25.75 | 5.01644E-03 |
| 25.55 | 3.7842E-03 |
| 25.35 | 4.60702E-03 |
| 25.15 | 4.62597E-03 |
| 24.95 | 4.56259E-03 |
| 24.75 | 4.61373E-03 |
| 24.55 | 1.85203E-03 |
| 24.35 | 5.21961E-03 |
| 24.15 | 3.61902E-03 |
| 23.95 | 3.5556E-03 |
| 23.75 | 3.66847E-03 |
| 23.55 | 3.09298E-03 |
| 23.35 | 4.00136E-03 |
| 23.15 | 3.80102E-03 |
| 22.95 | 3.97823E-03 |
| 22.75 | 3.58884E-03 |
| 22.55 | 3.48468E-03 |
| 22.35 | 3.87432E-03 |
| 22.15 | 3.29024E-03 |
| 21.95 | 3.63142E-03 |
| 21.75 | 3.06144E-03 |
| 21.55 | 4.20018E-03 |
| 21.35 | 4.4768E-03 |
| 21.15 | 4.28236E-03 |
| 20.95 | 3.00664E-03 |
| 20.75 | 3.25279E-03 |
| 20.55 | 3.37913E-03 |
| 20.35 | 1.90121E-03 |
| 20.15 | 1.99829E-03 |

T-2

| | |
|---|---|
| 33.23 | 1.66832E-04 |
| 33.03 | 6.90395E-04 |
| 32.8299 | 1.7976E-03 |
| 32.6299 | 1.86723E-03 |
| 32.43 | 2.57152E-03 |
| 32.23 | 3.1981E-03 |
| 32.03 | 5.73566E-03 |
| 31.8299 | 7.02609E-03 |
| 31.63 | 2.05525E-02 |
| 31.03 | 5.07366E-03 |
| 30.8299 | 2.17481E-03 |
| 30.63 | 1.23263E-03 |
| 30.4299 | 6.62427E-04 |
| 30.23 | 5.23249E-04 |
| 30.03 | 4.37842E-04 |

```
 29.8299                 4.10707E-04
 29.63                 3.85072E-04
 29.4299                 3.37759E-04
 29.23                 2.91436E-04
 29.03                 3.58112E-04
 28.8299                 3.56916E-04
 28.63                 3.66127E-04
 28.4299                 3.04678E-04
 28.23                 2.7094E-04
 28.03                 3.58272E-04
 27.8299                 3.86485E-04
 27.63                 3.65848E-04
 27.4299                 5.18548E-04
 27.23                 9.2168E-04
 27.03                 8.13054E-04
 26.8299                 9.7518E-04
 26.63                 9.79955E-04
 26.4299                 9.5876E-04
 26.23                 1.02691E-03
 26.0299                 9.58223E-04
 25.8299                 9.78746E-04
 25.6299                 1.45215E-03
 25.43                 1.95376E-03
 25.23                 2.40442E-03
 25.03                 2.48236E-03
 24.83                 2.38119E-03
 24.63                 2.76879E-03
 24.43                 1.82916E-03
 24.23                 .001392
 24.03                 1.2398E-03
 23.83                 1.54149E-03
 23.63                 1.90681E-03


T-3


31.31                 2.14968E-03
 31.11                 2.89149E-03
 30.91                 3.68096E-03
 30.71                 4.10691E-03
 30.51                 3.23547E-03
 30.31                 2.60897E-03
 30.11                 2.23587E-03
 29.91                 2.03772E-03
 29.71                 2.3277E-03
 29.51                 1.20083E-03
 29.31                 1.14746E-03
 29.11                 6.67011E-04
 28.91                 1.03744E-03
 28.71                 8.08642E-04
 28.51                 1.39021E-03
 28.31                 9.88095E-04
 28.11                 1.09086E-03
 27.91                 1.21687E-03
 27.71                 1.0203E-03
 27.51                 1.81924E-03
 27.31                 1.70628E-03
 27.11                 1.58881E-03
 26.91               2.45132E-03
 26.71               3.60023E-03
 26.51               4.14792E-03
 26.31               3.85714E-03
 26.11               2.81229E-03
 25.91               2.88185E-03
 25.71               3.34459E-03
 25.51               4.04696E-03
 25.31               3.5282E-03
 25.11               3.63912E-03
 24.91               3.44555E-03
 24.71               2.96623E-03
 24.51               2.15199E-03


T-4


19.6899               6.6379E-04
 19.49               6.52924E-04
 19.2899               1.67851E-04
 19.09               8.15463E-04
 18.89               1.08176E-03
 18.6899               3.85271E-04
 18.49               6.76149E-04
 18.2899               7.71252E-04
 18.09               5.34179E-04
 17.89               1.39774E-03
 17.6899               1.54529E-03
 17.49               9.74655E-04
 17.2899               5.73276E-04
 17.09               8.01585E-04
 16.89               1.20141E-03
 16.6899               1.74462E-03
 16.49               .001583
 16.2899               2.29876E-03
 16.09               1.19318E-03
 15.89               2.30504E-03
 15.69               8.17237E-04
 15.49               8.1569E-04
 15.2899               1.23431E-03
 15.0899               1.36089E-03
 14.89               1.99603E-03
 14.69               2.14831E-03
 14.49               2.34375E-03
 14.2899               5.95353E-04
 14.0899               3.94715E-03
 13.89               1.69436E-03
 13.69               1.93971E-03
 13.49               1.36123E-03
 13.2899               6.63664E-04
 13.0899               1.47207E-03
 12.8899               1.24379E-03
 12.69               1.37903E-03
 12.49               1.12586E-03
 12.29               1.53395E-03
 12.09               1.78363E-03
 11.89               2.50472E-03
 11.69               2.28191E-03
```

```
   11.49                          2.67024E-03
   11.29                          4.08482E-03
   11.09                          3.71615E-03
   10.89                          2.66683E-03
   10.69                          2.27763E-03
   10.49                          3.13575E-03
   10.29                          3.5148E-03
   10.09                          2.3527E-03


  T-5


  21.32                         7.64844E-04
   21.1199                          1.22024E-03
   20.92                          1.2658E-03
   20.72                          .001377
   20.52                          1.4446E-03
   20.32                          8.12634E-04
   20.1199                          1.44874E-03
   19.92                          1.13474E-03
   19.72                          8.43338E-04
   19.52                          5.50091E-04
   19.32                          7.3717E-04
   19.1199                         6.2405E-04
   18.92                          8.80784E-04
   18.72                          8.4838E-04
   18.52                          1.42485E-03
   18.32                          7.79341E-04
   18.1199                          9.04895E-04
   17.92                          7.60124E-04
   17.72                          8.52093E-04
   17.52                          6.91568E-04
   17.32                          7.58024E-04
   17.1199                          9.69085E-04
   16.92                          6.24837E-04
   16.72                          7.49744E-04
   16.52                          7.79722E-04
   16.32                          1.20274E-03
   16.1199                          1.10324E-03
   15.92                          9.40899E-04
   15.72                          9.01896E-04
   15.52                          7.83752E-04
   15.32                          6.10869E-04
   15.12                          6.21416E-04
   14.92                          7.22031E-04
   14.72                          5.34541E-04
   14.52                          5.29064E-04
   14.32                          9.13828E-04
   14.12                          9.05569E-04
   13.92                          8.77422E-04
   13.72                          6.05218E-04
   13.52                          6.55206E-04
   13.32                          8.64508E-04
   13.12                          1.30703E-03
   12.92                          7.87144E-04
   12.7199                          9.87459E-04
   12.5199                          7.95478E-04
   12.32                          9.552E-04
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12.12                9.27431E-04
11.92                6.12652E-04
11.7199                5.49242E-04
11.5199                8.23472E-04
11.32                9.85826E-04
11.12                5.36337E-04
```

## A.6 Correlated Permeameter and Packer-Slug Test Values.

The following data are correlated 20 cm correlated and averaged permeameter values with the corresponding 20 cm packer-slug test values. The data are presented by study site. All hydraulic conductivities are in cm/s. The installation factors (F/A) are also noted.

F/A = 6.54

C-1/T-1

| Slug test | Permeameter test |
|---|---|
| 4.73689E-03 | 2.61E-5 |
| 5.51517E-03 | 1.42E-4 |
| 4.57067E-03 | 4.57E-5 |
| 4.32716E-03 | 2.03E-4 |
| 2.40053E-03 | 1.80E-4 |
| 2.74304E-03 | 6.52E-4 |
| 2.70852E-03 | 1.30E-3 |
| 4.43019E-03 | 3.86E-5 |
| 4.36558E-03 | 4.08E-5 |
| 3.86071E-03 | 7.46E-5 |
| 4.01943E-03 | 1.48E-4 |
| 3.42966E-03 | 2.32E-3 |
| 3.35434E-03 | 1.66E-2 |
| 5.05651E-03 | 1.10E-2 |
| 3.31402E-03 | 8.59E-3 |
| 4.38128E-03 | 9.85E-4 |
| 5.4596E-03 | 1.30E-2 |
| 4.07976E-03 | 7.99E-3 |
| 4.49168E-03 | 1.90E-2 |
| 4.13202E-03 | 2.12E-2 |
| 4.77012E-03 | 3.34E-2 |
| 3.99151E-03 | 1.44E-2 |
| 4.31248E-03 | 1.05E-2 |
| 1.47868E-02 | 8.70E-3 |
| 1.18488E-02 | 1.10E-2 |
| 1.15924E-02 | 6.42E-2 |
| 1.08766E-02 | 1.76E-2 |
| .01003 | 9.50E-3 |
| 9.8926E-03 | 1.83E-2 |
| 1.00034E-02 | 1.44E-2 |
| 4.01556E-03 | 1.56E-2 |
| 1.13171E-02 | 1.21E-2 |
| 7.84674E-03 | 1.98E-2 |
| 7.95397E-03 | 1.08E-2 |
| 6.70619E-03 | 3.09E-2 |
| 8.67573E-03 | 7.81E-3 |
| 8.24136E-03 | 1.68E-2 |
| 8.62558E-03 | 1.17E-2 |
| 7.78132E-03 | 1.24E-2 |
| 7.55548E-03 | 1.86E-2 |
| 7.13389E-03 | 1.84E-2 |
| 7.87363E-03 | 2.84E-2 |
| 6.63781E-03 | 4.40E-2 |
| 9.10683E-03 | 1.60E-2 |
| 9.70658E-03 | 4.99E-3 |
| .009285 | 2.24E-3 |
| 7.05269E-03 | 9.48E-3 |

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 7.32661E-03 8.76E-3
 4.1222E-03  7.27E-3
 4.33269E-03 5.61E-3
```

C-2/T-2

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3.61725E-04   4.64E-2
3.89755E-03 2.19E-3
4.04853E-03 4.24E-3
5.57557E-03   2.80E-3
6.9341E-03    6.79E-3
.012436       1.63E-3
1.52339E-02 1.17E-4
1.10006E-02   1.45E-3
4.71542E-03 1.76E-3
2.67259E-03   6.60E-4
1.43627E-03 3.36E-4
1.1345E-03    9.47E-4
6.31892E-04   2.74E-3
7.76457E-04   1.57E-4
7.73864E-04 1.18E-4
7.93837E-04   1.73E-4
5.87451E-04   4.35E-3
7.76804E-04   7.30E-3
8.37975E-04 3.76E-3
7.9323E-04    2.55E-4
1.12431E-03 9.60E-4
1.99838E-03   9.82E-5
2.11438E-03 3.09E-4
2.12473E-03   9.43E-4
2.07877E-03 1.44E-3
2.22655E-03   1.01E-3
2.07761E-03 5.40E-4
2.12211E-03 5.22E-4
3.14855E-03 3.62E-3
5.21326E-03   1.74E-4
5.38224E-03   4.44E-5
5.1629E-03    9.74E-3
6.00329E-03   1.74E-2
3.96599E-03   2.45E-2
3.01814E-03   2.12E-2
```

C-3/T-3

```
4.66093E-03 3.66E-3
6.26933E-03 1.25E-3
7.98105E-03 1.47E-4
8.9046E-03  1.05E-3
7.01513E-03 5.14E-4
4.8478E-03  1.39E-4
5.04691E-03 2.03E-4
2.60364E-03 7.14E-5
2.48792E-03 4.07E-4
1.44621E-03 4.85E-4
2.24939E-03 3.68E-4
1.75329E-03 3.01E-4
```

```
3.01426E-03 1.58E-4
2.21221E-03 3.23E-4
3.94447E-03 1.14E-3
3.69955E-03 1.73E-3
3.44486E-03 3.47E-3
8.99351E-03 5.37E-3
8.36304E-03 6.00E-3
6.09759E-03 7.90E-3
6.24842E-03 8.52E-3
7.25174E-03 7.95E-3
8.77462E-03 8.31E-3
7.47063E-03 5.54E-3
6.43138E-03 5.84E-3
4.66595E-03 6.04E-3
```

C-4/T-4

```
1.43922E-03 3.12E-4
1.41566E-03 5.56E-4
3.63934E-04 8.69E-4
1.76808E-03 1.29E-3
2.34547E-03 9.33E-4
8.35344E-04 8.85E-4
1.46602E-03 6.02E-4
1.67222E-03 3.61E-4
1.1582E-03    1.60E-4
3.03057E-03  2.44E-4
3.3505E-03 2.44E-4
2.11324E-03    1.56E-4
1.24297E-03 6.26E-4
1.73799E-03    5.04E-4
2.60489E-03    7.25E-3
3.78269E-03  1.24E-3
3.43227E-03    9.16E-4
4.98416E-03  3.02E-4
4.99777E-03  7.76E-3
1.77193E-03 8.43E-3
1.76857E-03  7.00E-3
2.67623E-03  1.00E-2
2.95069E-03  1.89E-3
4.3278E-03    1.16E-3
4.65795E-03  2.02E-4
5.08171E-03 4.21E-4
1.29084E-03  1.61E-4
8.5582E-03  5.20E-3
3.67371E-03  6.26E-3
4.20568E-03  2.44E-3
2.95142E-03 2.67E-3
1.43895E-03 2.77E-3
3.19174E-03 2.65E-3
2.69678E-03  5.28E-3
.00299  4.68E-3
2.44109E-03  1.20E-3
3.32591E-03  3.63E-3
3.86726E-03  1.50E-3
5.43072E-03  1.94E-4
4.94763E-03  1.75E-3
5.78962E-03  4.92E-3
```

```
8.85671E-03  9.20E-3
8.05735E-03  8.91E-3
5.7822E-03  6.16E-3
4.93834E-03  3.56E-3
6.79892E-03  3.96E-3
7.62078E-03  5.41E-3


C-5/T-5


1.65833E-03 3.06E-3
2.64572E-03 1.65E-3
2.74451E-03 2.91E-3
2.98561E-03 1.97E-3
3.13219E-03 1.43E-3
1.76195E-03 6.38E-5
3.14116E-03 1.31E-4
2.46034E-03 1.40E-4
1.82852E-03 6.52E-5
1.1927E-03  1.47E-4
1.59833E-03 9.68E-5
1.35306E-03 7.78E-5
1.83945E-03 1.57E-4
3.08937E-03 6.48E-5
1.68976E-03 7.14E-5
1.96199E-03 9.60E-5
1.64809E-03 1.10E-4
1.8475E-03 1.91E-4
1.49945E-03 1.76E-4
2.10116E-03 3.44E-4
1.62559E-03 2.91E-4
1.69059E-03 9.88E-4
2.60778E-03 1.47E-4
2.39204E-03 5.49E-4
2.04005E-03 6.36E-3
1.95548E-03 5.67E-3
1.32448E-03 7.71E-3
1.5655E-03 1.12E-2
1.15899E-03 1.22E-2
1.98135E-03 2.10E-3
1.96345E-03 1.49E-3
1.90242E-03 9.16E-3
1.31223E-03 3.91E-4
1.42061E-03 5.54E-4
1.87442E-03 4.13E-4
2.8339E-03 1.66E-3
1.72475E-03 1.57E-3



F/A = 7.07


C-1/T-1


 4.38179E-03 2.61E-5
 5.10172E-03 1.42E-4
 4.22803E-03 4.57E-5
 4.00278E-03 2.03E-4
 2.22057E-03 1.80E-4
 2.53741E-03 6.52E-4
 2.50547E-03 1.30E-3
 4.09808E-03 3.86E-5
 4.03831E-03 4.08E-5
 3.57129E-03 7.46E-5
 3.71811E-03 1.48E-4
 3.17256E-03 2.32E-3
 3.10288E-03 1.66E-2
 4.67745E-03 1.10E-2
 3.06558E-03 8.59E-3
 4.05284E-03 9.85E-4
 5.05033E-03 1.30E-2
 3.77392E-03 7.99E-3
 4.15497E-03 1.90E-2
 3.82227E-03 2.12E-2
 4.41253E-03 3.34E-2
 3.69229E-03 1.44E-2
 3.98919E-03 1.05E-2
 1.36783E-02 8.70E-3
 1.09606E-02 1.10E-2
 1.07233E-02 6.42E-2
 1.00612E-02 1.76E-2
 9.27811E-03 9.50E-3
 .009151      1.83E-2
 9.25358E-03 1.44E-2
 3.71454E-03 1.56E-2
 1.04687E-02 1.21E-2
 7.25852E-03 1.98E-2
 7.3577E-03 1.08E-2
 6.20346E-03 3.09E-2
 8.02536E-03 7.81E-3
 7.62355E-03 1.68E-2
 7.97897E-03 1.17E-2
 7.19799E-03 1.24E-2
 6.98909E-03 1.86E-2
 6.5991E-03  1.84E-2
 7.28338E-03 2.84E-2
 6.14021E-03 4.40E-2
 8.42414E-03 1.60E-2
 8.97893E-03 4.99E-3
 8.58896E-03 2.24E-3
 6.52399E-03 9.48E-3
 6.77738E-03 8.76E-3
 3.81318E-03 7.27E-3
 4.00789E-03 5.61E-3


C-2/T-2


3.34609E-04 4.64E-2
3.60537E-03 2.19E-3
3.74503E-03 4.24E-3
5.1576E-03  2.80E-3
6.41429E-03 6.79E-3
1.15037E-02 1.63E-3
1.40919E-02 1.17E-4
```

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.010176      1.45E-3
4.36193E-03 1.76E-3
2.47224E-03 6.60E-4
1.3286E-03   3.36E-4
1.04945E-03 9.47E-4
5.84522E-04 2.74E-3
7.1825E-04   1.57E-4
7.15852E-04 1.18E-4
7.34327E-04 1.73E-4
5.43413E-04 4.35E-3
7.18571E-04 7.30E-3
7.75156E-04 3.76E-3
7.33766E-04 2.55E-4
1.04003E-03 9.60E-4
1.84857E-03 9.82E-5
1.95587E-03 3.09E-4
1.96545E-03 9.43E-4
1.92294E-03 1.44E-3
2.05963E-03 1.01E-3
1.92186E-03 5.40E-4
1.96303E-03 5.22E-4
2.91252E-03 3.62E-3
4.82245E-03 1.74E-4
4.97876E-03 4.44E-5
4.77586E-03 9.74E-3
5.55326E-03 1.74E-2
3.66868E-03 2.45E-2
2.79188E-03 2.12E-2
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C-3/T-3

```
4.31153E-03 3.66E-3
5.79935E-03 1.25E-3
7.38276E-03 1.47E-4
8.23707E-03 1.05E-3
6.48925E-03 5.14E-4
4.48439E-03 1.39E-4
4.66857E-03 2.03E-4
2.40846E-03 7.14E-5
2.30141E-03 4.07E-4
1.33779E-03 4.85E-4
2.08076E-03 3.68E-4
1.62186E-03 3.01E-4
2.7883E-03   1.58E-4
2.04638E-03 3.23E-4
3.64878E-03 1.14E-3
3.42221E-03 1.73E-3
3.18662E-03 3.47E-3
8.31932E-03 5.37E-3
7.73611E-03 6.00E-3
5.64049E-03 7.90E-3
5.78001E-03 8.52E-3
6.70812E-03 7.95E-3
8.11683E-03 8.31E-3
6.9106E-03   5.54E-3
5.94926E-03 5.84E-3
4.31617E-03 6.04E-3
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C-4/T-4

```
1.33133E-03 3.12E-4
1.30954E-03   5.56E-4
3.36652E-04 8.69E-4
1.63554E-03 1.29E-3
2.16964E-03 9.33E-4
7.72722E-04 8.85E-4
1.35612E-03   6.02E-4
1.54686E-03 3.61E-4
1.07138E-03   1.60E-4
2.80339E-03   2.44E-4
3.09933E-03 2.44E-4
1.95482E-03   1.56E-4
1.14979E-03 6.26E-4
1.6077E-03    5.04E-4
2.40962E-03   7.25E-3
3.49913E-03 1.24E-3
3.17497E-03   9.16E-4
4.61052E-03 3.02E-4
4.62312E-03   7.76E-3
1.63909E-03 8.43E-3
1.63599E-03 7.00E-3
2.47561E-03 1.00E-2
2.72949E-03 1.89E-3
4.00336E-03   1.16E-3
4.30877E-03   2.02E-4
4.70077E-03   4.21E-4
1.19407E-03 1.61E-4
7.91664E-03 5.20E-3
3.39831E-03   6.26E-3
3.8904E-03    2.44E-3
2.73017E-03   2.67E-3
1.33108E-03   2.77E-3
2.95247E-03   2.65E-3
2.49462E-03   5.28E-3
2.76586E-03    4.68E-3
2.25809E-03   1.20E-3
3.07658E-03   3.63E-3
3.57735E-03   1.50E-3
5.02361E-03   1.94E-4
4.57673E-03   1.75E-3
5.3556E-03    4.924E-3
8.19277E-03   9.20E-3
7.45333E-03   8.91E-3
5.34874E-03   6.16E-3
4.56814E-03   3.56E-3
6.28924E-03   3.96E-3
7.04949E-03   5.41E-3
```

C-5/T-5

```
 1.53401E-03 3.06E-3
 2.44739E-03 1.65E-3
 2.53877E-03 2.91E-3
 2.76179E-03 1.97E-3
 2.89739E-03 1.43E-3
 1.62986E-03 6.38E-5
 2.90568E-03 1.31E-4
 2.2759E-03 1.40E-4
 1.69144E-03 6.52E-5
 1.10329E-03 1.47E-4
 1.47851E-03 9.68E-5
 1.25163E-03 7.78E-5
 1.70156E-03 1.57E-4
 2.85777E-03 6.48E-5
 1.56309E-03 7.14E-5
 1.81491E-03 9.60E-5
 1.52455E-03 1.10E-4
 .001709 1.91E-4
  1.38704E-03 1.76E-4
 1.94365E-03 3.44E-4
 1.50372E-03 2.91E-4
 1.56385E-03 9.88E-4
 2.41229E-03 1.47E-4
 2.21272E-03 5.49E-4
 1.88712E-03 6.36E-3
 1.80889E-03 5.67E-3
 1.22519E-03 7.71E-3
 1.44814E-03 1.12E-2
 1.0721E-03 1.22E-2
 1.83282E-03 2.10E-3
 1.81626E-03 1.49E-3
 1.7598E-03 9.16E-3
 1.21386E-03 3.91E-4
  1.31411E-03 5.54E-4
  1.7339E-03 4.13E-4
 2.62145E-03 1.66E-3
 1.59545E-03 1.57E-3


F/A = 14.18


C-1/T-1


2.18471E-03 2.61E-5
2.54366E-03 1.42E-4
2.10805E-03 4.57E-5
1.99574E-03 2.03E-4
1.10715E-03 1.80E-4
1.26512E-03 6.52E-3
1.2492E-03  1.30E-3
2.04326E-03 3.86E-5
2.01346E-03 4.08E-5
1.78061E-03 7.46E-5
1.85381E-03 1.48E-4
1.5818E-03  2.32E-3
1.54706E-03 1.66E-2
2.33213E-03 1.10E-2
1.52846E-03 8.59E-3
2.0207E-03 9.85E-4
2.51804E-03 1.30E-2
1.88164E-03 7.99E-3
```

```
2.07162E-03 1.90E-2
1.90574E-03 2.12E-2
2.20004E-03 3.34E-2
1.84093E-03 1.44E-2
1.98897E-03 1.05E-2
6.81988E-03 8.70E-3
5.46485E-03 1.10E-2
5.34656E-03 6.42E-2
5.01644E-03 1.76E-2
4.62597E-03 9.50E-3
4.56259E-03 1.83E-2
4.61373E-03 1.44E-2
1.85203E-03 1.56E-2
5.21961E-03 1.21E-2
3.61902E-03 1.98E-2
3.66847E-03 1.08E-2
3.09298E-03 3.09E-2
4.00136E-03 7.81E-3
3.80102E-03 1.68E-2
3.97823E-03 1.17E-2
3.58884E-03 1.24E-2
3.48468E-03 1.86E-2
3.29024E-03 1.84E-2
3.63142E-03 2.84E-2
3.06144E-03 4.40E-2
4.20018E-03 1.60E-2
4.4768E-03 4.99E-3
4.28236E-03 2.24E-3
3.25279E-03 9.48E-3
3.37913E-03 8.76E-3
1.90121E-03 7.27E-3
1.99829E-03 5.61E-3
```

C-2/T-2

```
1.66832E-04 4.64E-2
1.7976E-03 2.19E-3
1.86723E-03 4.24E-3
2.57152E-03 2.80E-3
3.1981E-03 6.79E-3
5.73566E-03 1.63E-3
7.02609E-03 1.17E-4
5.07366E-03 1.45E-3
2.17481E-03 1.76E-3
1.23263E-03 6.60E-4
6.62427E-04 3.36E-4
5.23249E-04 9.47E-4
2.91436E-04 2.74E-3
3.58112E-04 1.57E-4
3.56916E-04 1.18E-4
3.66127E-04 1.73E-4
2.7094E-04  4.35E-3
3.58272E-04 7.30E-3
3.86485E-04 3.76E-3
3.65848E-04 2.55E-4
5.18548E-04 9.60E-4
9.2168E-04 9.82E-5
9.7518E-04 3.09E-4
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9.79955E-04 9.43E-4
9.5876E-04 1.44E-3
1.02691E-03 1.01E-3
9.58223E-04 5.40E-4
9.78746E-04 5.22E-4
1.45215E-03 3.62E-3
2.40442E-03 1.74E-4
2.48236E-03 4.44E-5
2.38119E-03 9.74E-3
2.76879E-03 1.74E-2
1.82916E-03 2.45E-2
.001392 2.12E-2
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C-3/T-3

```
   2.14968E-03 3.66E-3
   2.89149E-03 1.25E-3
   3.68096E-03 1.47E-4
   4.10691E-03 1.05E-3
   3.23547E-03 5.14E-4
   2.23587E-03 1.39E-4
   2.3277E-03  2.03E-4
   1.20083E-03 7.14E-5
   1.14746E-03 4.07E-4
 6.67011E-04 4.85E-4
    1.03744E-03 3.68E-4
    8.08642E-04 3.01E-4
     1.39021E-03 1.58E-4
   1.0203E-03  3.23E-4
   1.81924E-03 1.14E-3
   1.70628E-03 1.73E-3
    1.58881E-03 3.47E-3
  4.14792E-03 5.37E-3
  3.85714E-03 6.00E-3
 2.81229E-03 7.90E-3
    2.88185E-03 8.52E-3
    3.34459E-03 7.95E-3
 4.04696E-03 8.31E-3
  3.44555E-03 5.54E-3
  2.96623E-03 5.84E-3
 2.15199E-03 6.04E-3
```

C-4/T-4

```
6.6379E-04 3.12E-4
6.52924E-04  5.56E-4
1.67851E-04 8.69E-4
8.15463E-04   1.29E-3
1.08176E-03   9.33E-4
3.85271E-04 8.85E-4
6.76149E-04   6.02E-4
7.71252E-04 3.61E-4
5.34179E-04   1.60E-4
1.39774E-03   2.44E-4
1.54529E-03 2.44E-4
9.74655E-04   1.56E-4
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5.73276E-04 6.26E-4
8.01585E-04   5.04E-4
1.20141E-03   7.25E-3
1.74462E-03 1.24E-3
.001583       9.16E-4
2.29876E-03 3.02E-4
2.30504E-03   7.76E-3
8.17237E-04   8.43E-3
8.1569E-04    7.00E-3
1.23431E-03 1.00E-2
1.36089E-03 1.89E-3
1.99603E-03   1.16E-3
2.14831E-03   2.02E-4
2.34375E-03   4.21E-4
5.95353E-04 1.61E-4
3.94715E-03 5.20E-3
1.69436E-03   6.26E-3
1.93971E-03   2.44E-3
1.36123E-03   2.67E-3
6.63664E-04 2.77E-3
1.47207E-03  2.65E-3
1.24379E-03  5.28E-3
1.37903E-03    4.68E-3
1.12586E-03    1.20E-3
1.53395E-03    3.63E-3
1.78363E-03    1.50E-3
2.50472E-03    1.94E-4
2.28191E-03    1.75E-3
2.67024E-03    4.92E-3
4.08482E-03    9.20E-3
3.71615E-03    8.91E-3
2.66683E-03    6.16E-3
2.27763E-03    3.56E-3
3.13575E-03    3.69E-3
3.5148E-03     5.41E-3
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C-5/T-5

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 7.64844E-04 3.06E-3
1.22024E-03 1.65E-3
1.2658E-03 2.91E-3
.001377 1.97E-3
 1.4446E-03 1.43E-3
   8.12634E-04 6.38E-5
1.44874E-03 1.31E-4
   1.13474E-03 1.40E-4
8.43338E-04 6.52E-5
   5.50091E-04 1.47E-4
   7.3717E-04 9.68E-5
   6.2405E-04 7.78E-5
  8.4838E-04 1.57E-4
  1.42485E-03 6.48E-5
  7.79341E-04 7.14E-5
  9.04895E-04 9.60E-5
   7.60124E-04 1.10E-4
   8.52093E-04 1.91E-4
    6.91568E-04 1.76E-4
    9.69085E-04 3.44E-4
 7.49744E-04 2.91E-4
 7.79722E-04 9.88E-4
  1.20274E-03 1.47E-4
  1.10324E-03 5.49E-4
 9.40899E-04 6.36E-3
 9.01896E-04 5.67E-3
 6.10869E-04 7.71E-3
 7.22031E-04 1.12E-2
5.34541E-04 1.22E-2
9.13828E-04 2.10E-3
9.05569E-04 1.49E-3
8.77422E-04 9.16E-3
6.05218E-04 3.91E-4
  6.55206E-04 5.54E-4
  8.64508E-04 4.13E-4
1.30703E-03 1.66E-3
7.95478E-04 1.57E-3
```

## A.7 Statistical Data for All Methods.

```
C1  HYDRAULIC CONDUCTIVITIES

NUMBER OF VALUES :   231

   AVERAGE      MEAN      VARIANCE

  0.0101923  -5.8630627   5.2302795


                   MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0028425   0.0388548   0.0002080




C2  HYDRAULIC CONDUCTIVITIES

NUMBER OF VALUES :   171

   AVERAGE      MEAN      VARIANCE

  0.0055060  -6.6965878   3.6006030


                   MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0012351   0.0074743   0.0002041




C3  HYDRAULIC CONDUCTIVITIES

NUMBER OF VALUES :   158

   AVERAGE      MEAN      VARIANCE

  0.0036256  -6.4268469   2.6919394


                   MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0016175   0.0062145   0.0004210
```

```
C4  HYDRAULIC CONDUCTIVITIES

NUMBER OF VALUES :    229

   AVERAGE      MEAN      VARIANCE

  0.0027021  -7.0300531   3.1742176


                    MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0008849   0.0043267   0.0001810




C5  HYDRAULIC CONDUCTIVITIES

NUMBER OF VALUES :    164

   AVERAGE      MEAN      VARIANCE

  0.0020447  -7.6638448   3.3469155


                    MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0004695   0.0025027   0.0000881
```

```
C1 20cm AVERAGED HYD. COND.

NUMBER OF VALUES :     50

   AVERAGE      MEAN      VARIANCE

  0.0121439  -5.4313033   4.4660609


                  MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0043774   0.0408327   0.0004693




C2 20cm AVERAGE HYD. COND.

NUMBER OF VALUES :     35

   AVERAGE      MEAN      VARIANCE

  0.0048764  -6.6582328   3.0436080


                  MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0012834   0.0058786   0.0002802




C3 20cm AVERAGE HYD. COND.

NUMBER OF VALUES :     26

   AVERAGE      MEAN      VARIANCE

  0.0029572  -6.7134445   2.4621839


                  MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0012145   0.0041595   0.0003546
```

```
C4 20cm AVERAGE HYD. COND.

NUMBER OF VALUES :     47

   AVERAGE       MEAN      VARIANCE

  0.0029106  -6.5198099   1.7351743


                  MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0014739   0.0035097   0.0006190



C5 20cm AVERAGE HYD. COND.

NUMBER OF VALUES :     37

   AVERAGE       MEAN      VARIANCE

  0.0020380  -7.4515610   2.8459459


                  MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0005805   0.0024089   0.0001399
```

```
C1 HAZEN HYDRAULIC CONDUCTIVITIE

NUMBER OF VALUES :     53

   AVERAGE      MEAN      VARIANCE

  0.0925069  -5.4613369   6.9793963


                   MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0042479   0.1392285   0.0001296




C2  HAZEN HYDRAULIC CONDUCTIVITI

NUMBER OF VALUES :     35

   AVERAGE      MEAN      VARIANCE

  0.3034806  -5.7167536   8.0924445


                   MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0032904   0.1881470   0.0000575




C3  HAZEN HYDAULIC CONDUCTIVITIE

NUMBER OF VALUES :     32

   AVERAGE      MEAN      VARIANCE

  0.0032119  -6.6207569   3.3453443


                   MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0013324   0.0070970   0.0002502
```

```
C4  HAZEN HYDRAULIC CONDUCTIVITI

NUMBER OF VALUES :     45

   AVERAGE      MEAN      VARIANCE

  0.0025065  -7.4012500   5.3313291


                  MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0006105   0.0087773   0.0000425




C5  HAZEN HYDRAULIC CONDUCTIVITI

NUMBER OF VALUES :     38

   AVERAGE      MEAN      VARIANCE

  0.0038322  -6.4766961   2.4480685


                  MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0015389   0.0052336   0.0004525
```

```
1 K-permeameter correlated with SAMPLES FROM THE HAZEN METHOD
NUMBER OF VALUES :     53
  AVERAGE      MEAN      VARIANCE
 0.0113271  -5.7629156   4.8333182


                  MEANS
  GEOMETRIC  ARITHMETIC    HARMONIC
 0.0031419   0.0352159   0.0002803


C2 K-permeameter correlated with
UMBER OF VALUES :     35
  AVERAGE      MEAN      VARIANCE
 0.0059021  -6.8574899   4.2529407


                  MEANS
  GEOMETRIC  ARITHMETIC    HARMONIC
 0.0010515   0.0088175   0.0001254

C3 K-permeameter correlated with
NUMBER OF VALUES :     32
  AVERAGE      MEAN      VARIANCE
 0.0035445  -6.7220664   3.7609395


                  MEANS
  GEOMETRIC  ARITHMETIC    HARMONIC
 0.0012040   0.0078944   0.0001836
```

```
C4 K-permeameter correlated with

NUMBER OF VALUES :     45

   AVERAGE       MEAN       VARIANCE

  0.0029067  -7.2403514   4.5038825


                   MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0007171   0.0068165   0.0000754


C5 K-permeameter correlated with

NUMBER OF VALUES :     38

   AVERAGE       MEAN       VARIANCE

  0.0032675  -7.1358287   4.0656608


                   MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0007961   0.0060785   0.0001043
```

```
T1   HYDRAULIC CONDUCTIVITIES  F/A = 6.54

NUMBER OF VALUES :     64

   AVERAGE      MEAN      VARIANCE

  0.0064975  -5.1198935   0.1721071


                    MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0059767   0.0065137   0.0054839




T1  HYDRAULIC CONDUCTIVITIES  F/A = 7.07

NUMBER OF VALUES :     64

   AVERAGE      MEAN      VARIANCE

  0.0059914  -5.2034431   0.1778117


                    MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0054976   0.0060088   0.0050299




T1  HYDRAULIC CONDUCTIVITIES  F/A = 14,18

NUMBER OF VALUES :     64

   AVERAGE      MEAN      VARIANCE

  0.0029967  -5.8937877   0.1721081


                    MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC
```

(cont. next page)

```
  0.0027565   0.0030042   0.0025292



T2   HYDRAULIC CONDUCTIVITIES   F/A = 6.54

NUMBER OF VALUES :     47

   AVERAGE      MEAN      VARIANCE

  0.0040313  -6.0961592   0.9999725


                 MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0022515   0.0037120   0.0013656



T2   HYDRAULIC CONDUCTIVITIES   F/A = 7.07

NUMBER OF VALUES :     47

   AVERAGE      MEAN      VARIANCE

  0.0037291  -6.1740815   0.9999729


                 MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0020827   0.0034338   0.0012632
```

```
T2  HYDRAULIC CONDUCTIVITIES  F/A = 14.18

NUMBER OF VALUES :     47

   AVERAGE      MEAN      VARIANCE

  0.0018593  -6.8700557   0.9999734


                   MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0010384   0.0017120   0.0006298




T3  HYDRAULIC CONDUCTIVITIES  F/A = 6.54

NUMBER OF VALUES :     35

   AVERAGE      MEAN      VARIANCE

  0.0051932  -5.3828561   0.2811630


                   MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0045947   0.0052882   0.0039921




T3  HYDRAULIC CONDUCTIVITIES  F/A = 7.07

NUMBER OF VALUES :     35

   AVERAGE      MEAN      VARIANCE

  0.0048039  -5.4607784   0.2811633


                   MEANS  (cont next page)
   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0042502   0.0048918   0.0036928




T3  HYDRAULIC CONDUCTIVITIES  F/A= 14.18

NUMBER OF VALUES :    35

   AVERAGE      MEAN      VARIANCE

  0.0023951  -6.1567509   0.2811629


                  MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0021191   0.0024390   0.0018412




T4  HYDRAULIC CONDUCTIVITIES  F/4= 6.54

NUMBER OF VALUES :    49

   AVERAGE      MEAN      VARIANCE

  0.0035412  -5.8287256   0.4292946


                  MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0029418   0.0036462   0.0023735
```

```
T4  HYDRAULIC CONDUCTIVITIES  F/A = 7.07

NUMBER OF VALUES :    49

   AVERAGE     MEAN     VARIANCE

  0.0032757  -5.9066492   0.4292946


                    MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0027213   0.0033728   0.0021956




T4  HYDRAULIC CONDUCTIVITIES  F/A = 14.18

NUMBER OF VALUES :    49

   AVERAGE     MEAN     VARIANCE

  0.0016332  -6.6026228   0.4292934


                    MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0013568   0.0016817   0.0010947




T5  HYDRAULIC CONDUCTIVITIES  F/A = 6.54

NUMBER OF VALUES :    52

   AVERAGE     MEAN     VARIANCE

  0.0018883  -6.3095057   0.0747416


                    MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC (cont next page)
  0.0018189    0.0018882    0.0017522



T5  HYDRAULIC CONDUCTIVITIES  F/A = 7.07

NUMBER OF VALUES :     52

   AVERAGE      MEAN      VARIANCE

  0.0017467  -6.3874304   0.0747417


                     MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0016826    0.0017466    0.0016209



T5  HYDRAULIC CONDUCTIVITIES  F/A =14,18

NUMBER OF VALUES :     52

   AVERAGE      MEAN      VARIANCE

  0.0008709  -7.0833992   0.0747407


                     MEANS

   GEOMETRIC  ARITHMETIC    HARMONIC

  0.0008389    0.0008709    0.0008081
```

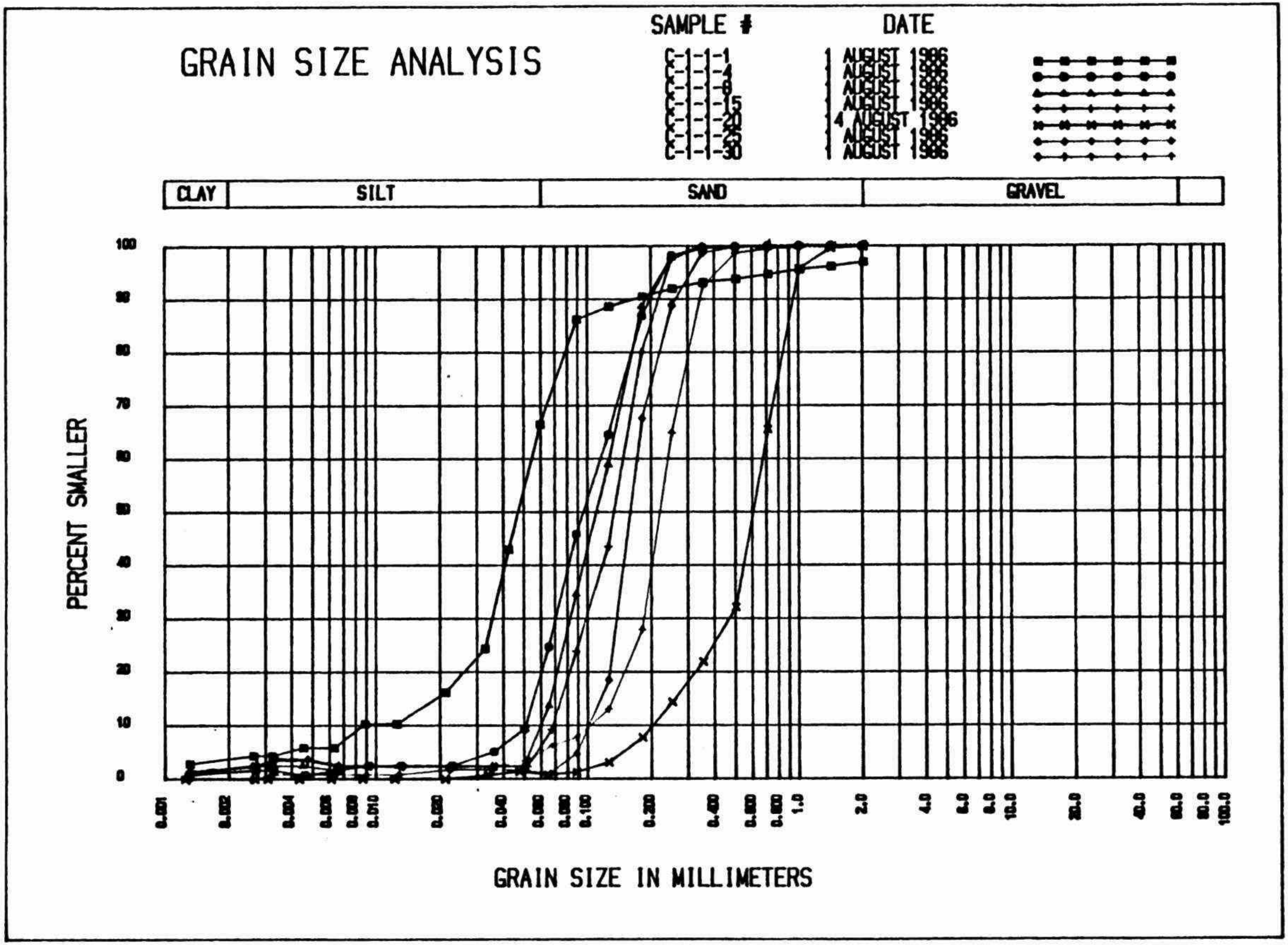
# Appendix B

# GRAIN-SIZE CURVES

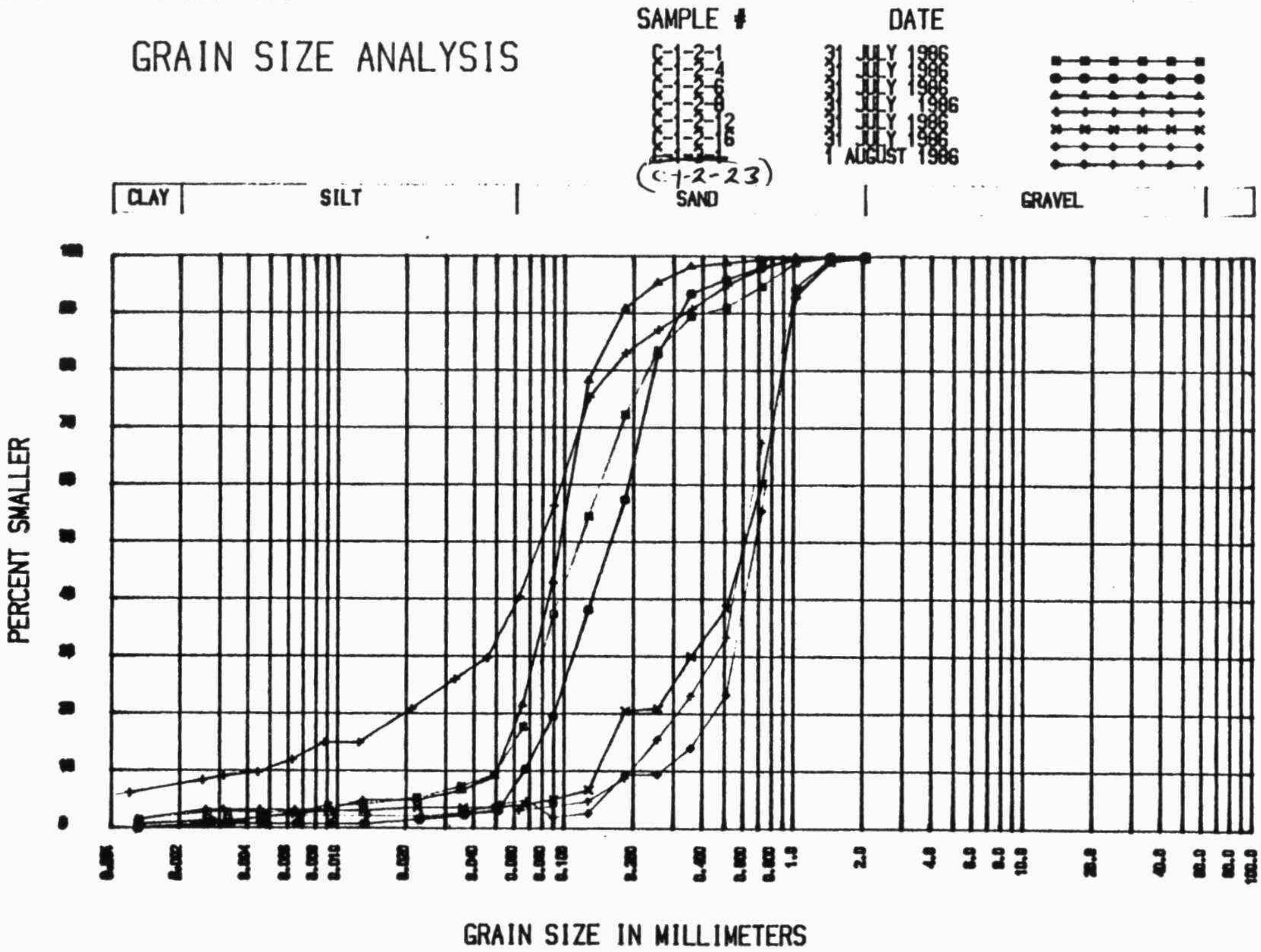
The following grain-size curves were plotted for each core from the five study sites. Only those data used in the permeameter tests and grain-size analyses for the Hazen method are presented here. The analyses were performed using Standard Canadian Sieves at 1/2 Phi intervals.

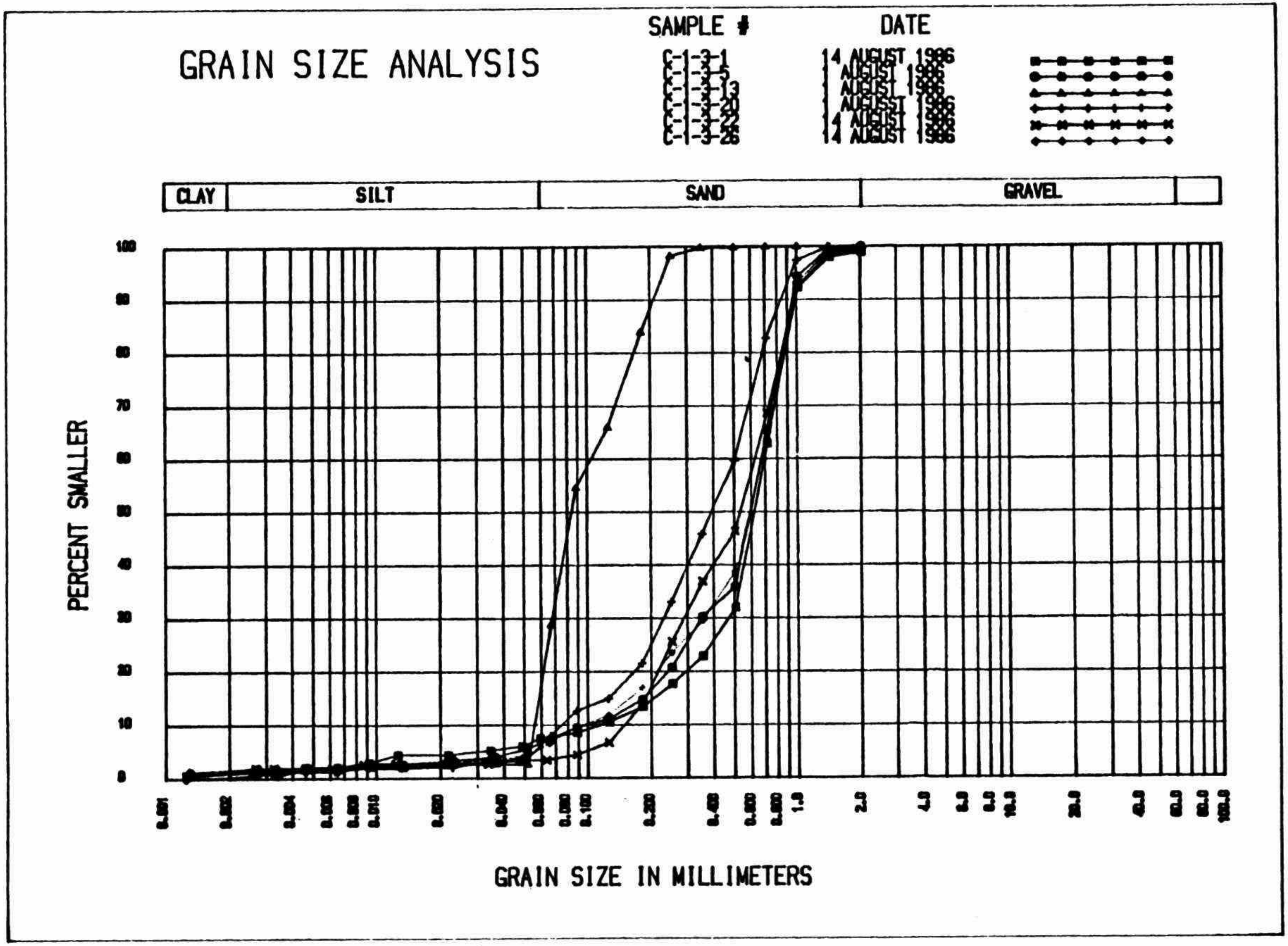
The code used for each sample is as follows; C = core, the first numeric label is the site (1-5), the second numeric label is the core within a site, and the third numeric label is the sample reference number. For example, C-1-1-4, is core hole number one, core one, and sample number four. Each sample was numbered from the top to the bottom of the core in 5 cm intervals and the cores were numbered as they were obtained in the field, ie., from the top to the bottom of the cored interval.

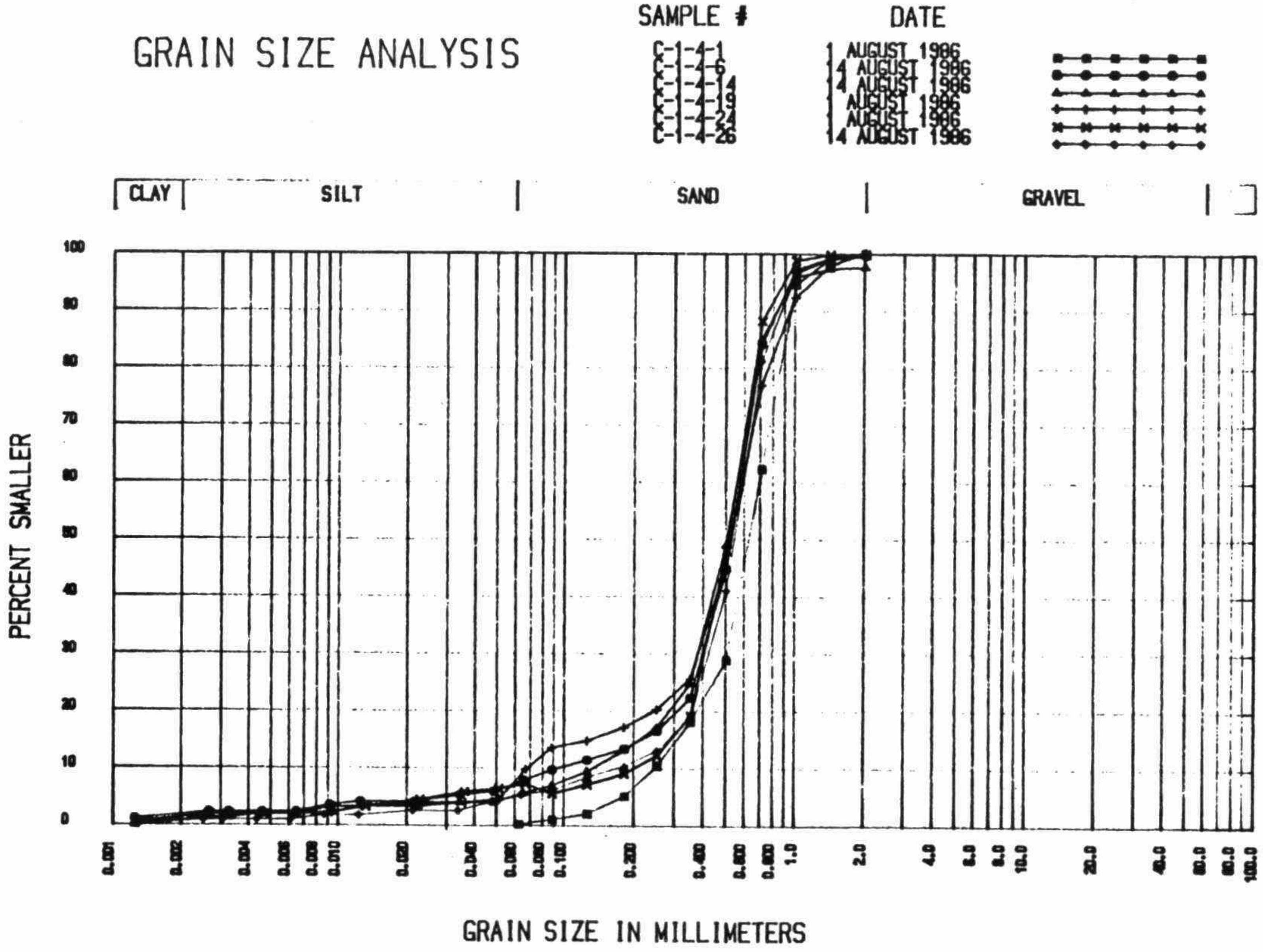
Note that for site C-5, cores C-5-3A and C-5-3B come before C-5-3. Cores C-5-1, 2, 3A, and 3B were taken before the Waterloo cohesionless aquifer core barrel was developed.


GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-1-1-1
C-1-1-4
C-1-1-8
C-1-1-15
C-1-1-20
C-1-1-25
C-1-1-30
1 AUGUST 1986
1 AUGUST 1986
1 AUGUST 1986
1 AUGUST 1986
4 AUGUST 1986
1 AUGUST 1986
1 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
0
10
20
30
40
50
60
70
80
90
100
0.001
0.002
0.004
0.006
0.008
0.010
0.020
0.040
0.060
0.080
0.100
0.200
0.400
0.600
0.800
1.0
2.0
4.0
6.0
8.0
10.0
20.0
40.0
60.0
80.0
100.0
GRAIN SIZE IN MILLIMETERS

# GRAIN SIZE ANALYSIS

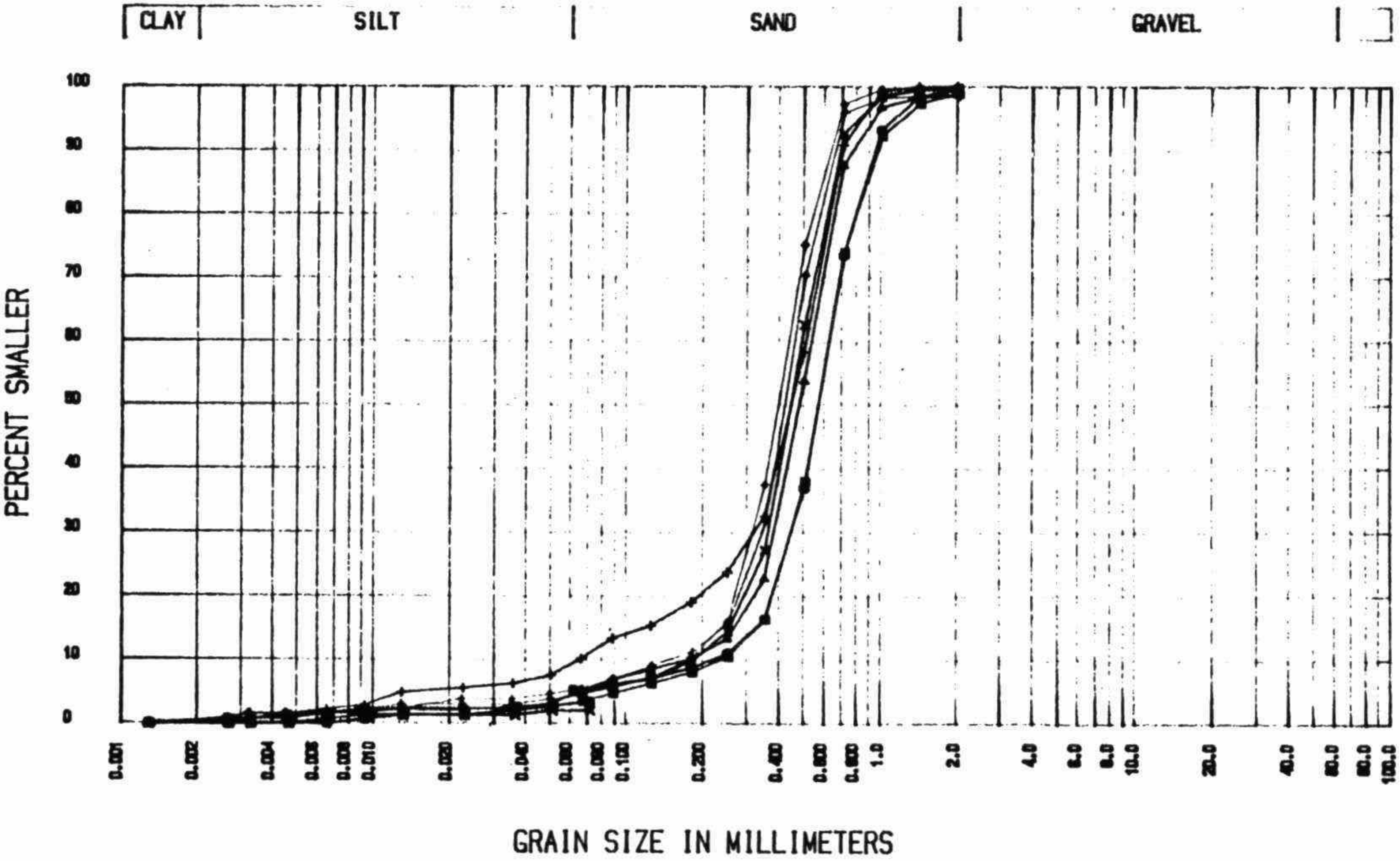



GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-1-3-1 14 AUGUST 1986 ■
C-1-3-5 14 AUGUST 1986 ●
C-1-3-13 14 AUGUST 1986 ▲
C-1-3-20 14 AUGUST 1986 +
C-1-3-22 14 AUGUST 1986 ×
C-1-3-26 14 AUGUST 1986 ◆
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
100
90
80
70
60
50
40
30
20
10
0
0.001
0.002
0.004
0.006
0.008
0.010
0.020
0.040
0.060
0.080
0.100
0.200
0.400
0.600
0.800
1.0
2.0
4.0
6.0
8.0
10.0
20.0
40.0
60.0
80.0
100.0
GRAIN SIZE IN MILLIMETERS


GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-1-4-1 1 AUGUST 1986 ■
C-1-4-6 14 AUGUST 1986 ●
C-1-4-14 14 AUGUST 1986 ▲
C-1-4-19 1 AUGUST 1986 +
C-1-4-24 1 AUGUST 1986 ✖
C-1-4-26 14 AUGUST 1986 ◆
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
100
90
80
70
60
50
40
30
20
10
0
0.001
0.002
0.004
0.006
0.008
0.010
0.020
0.040
0.060
0.080
0.100
0.200
0.400
0.600
0.800
1.0
2.0
4.0
6.0
8.0
10.0
20.0
40.0
60.0
80.0
100.0
GRAIN SIZE IN MILLIMETERS

# GRAIN SIZE ANALYSIS

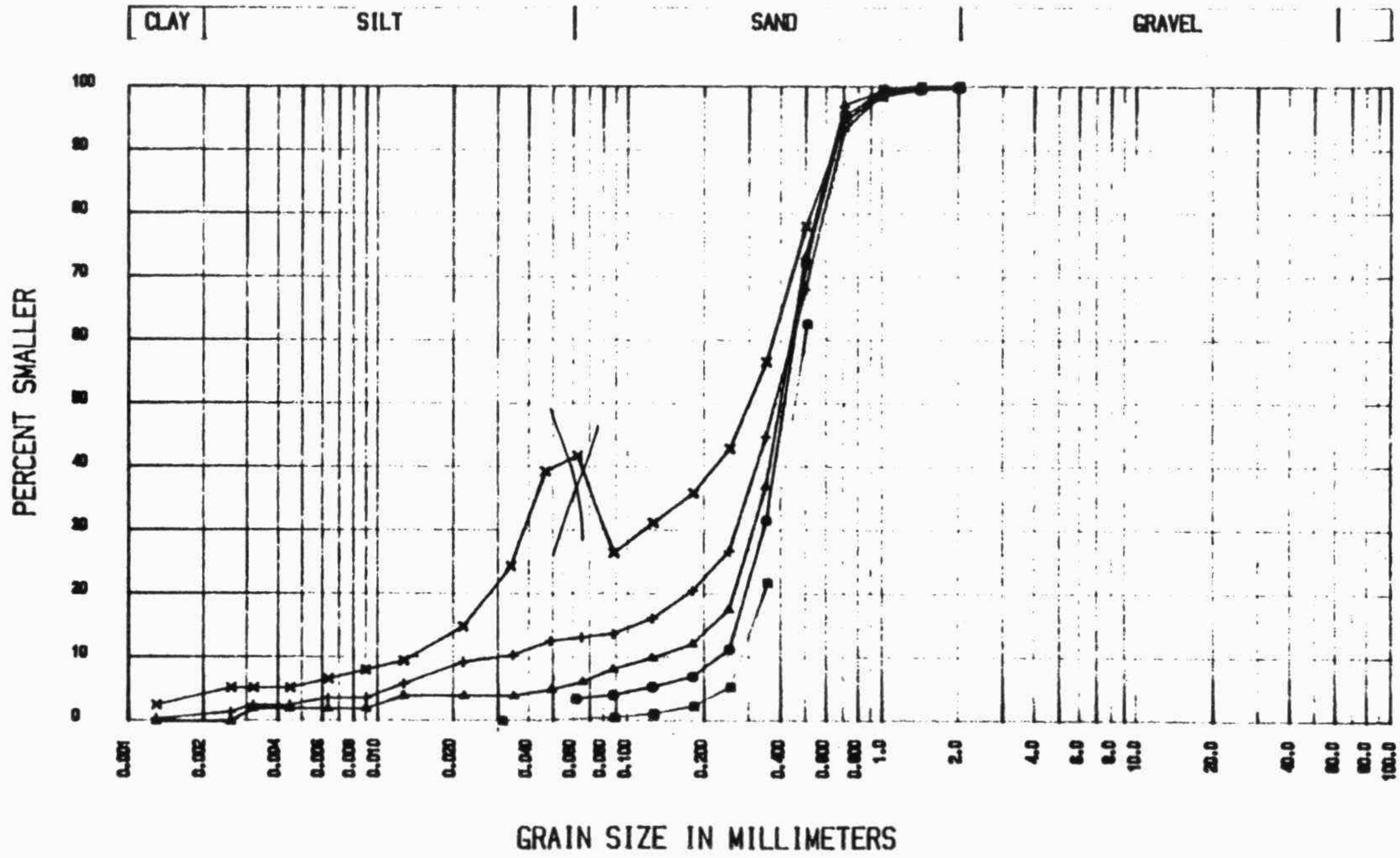
| SAMPLE # | DATE | |
|---|---|---|
| C-1-5-1 | 5 AUGUST 1986 | ■—■—■ |
| ~~C188~~ C-1-5-4 | 31 JULY 1986 | ●—●—● |
| C-1-5-6 | 5 AUGUST 1986 | ▲—▲—▲ |
| C-1-5-11 | 5 AUGUST 1986 | +—+—+ |
| C-1-5-15 | 31 JULY 1986 | ×—×—× |
| C-1-5-20 | 5 AUGUST 1986 | ◆—◆—◆ |
| C-1-5-23 | 5 AUGUST 1986 | ◆—◆—◆ |

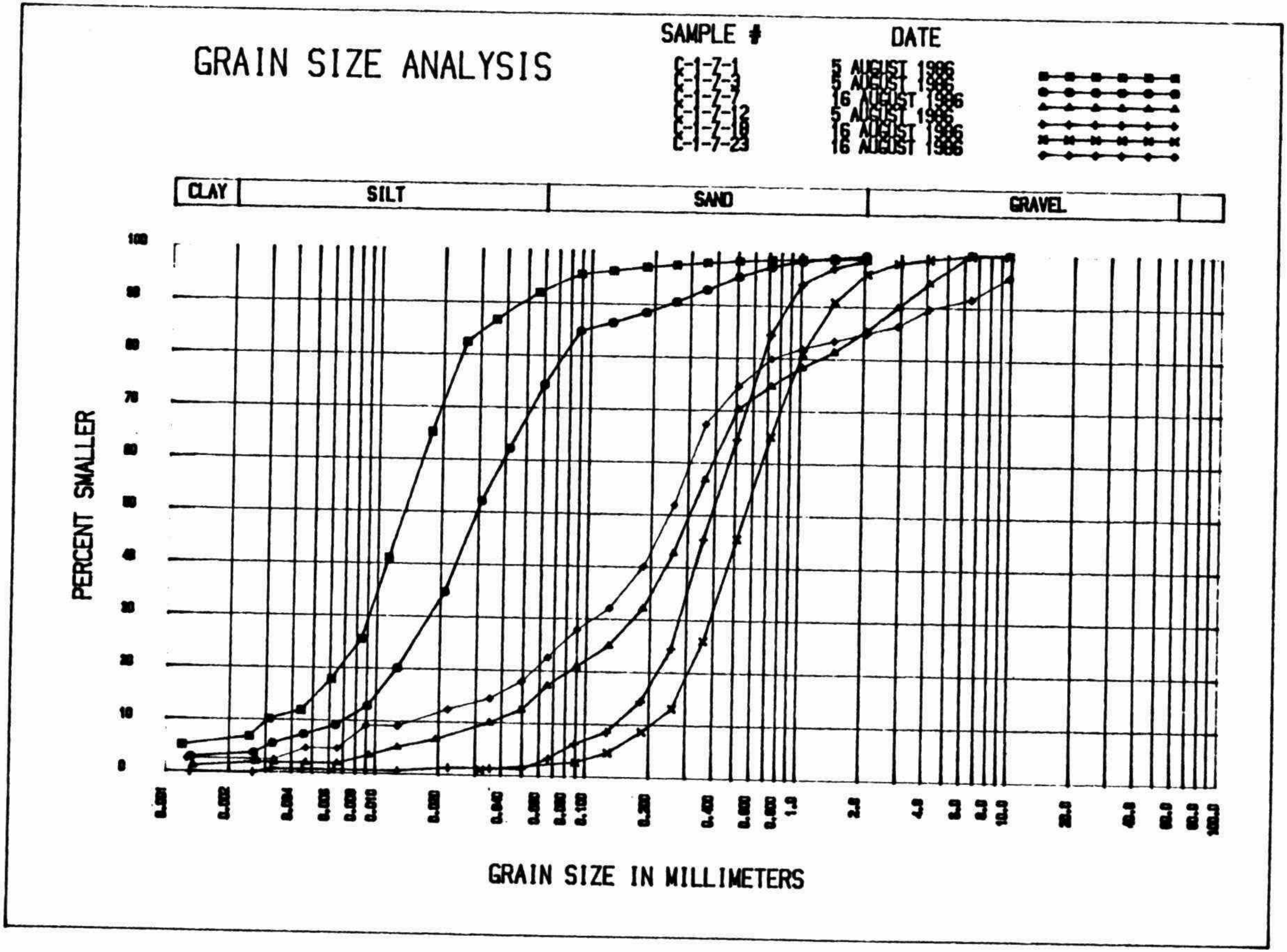


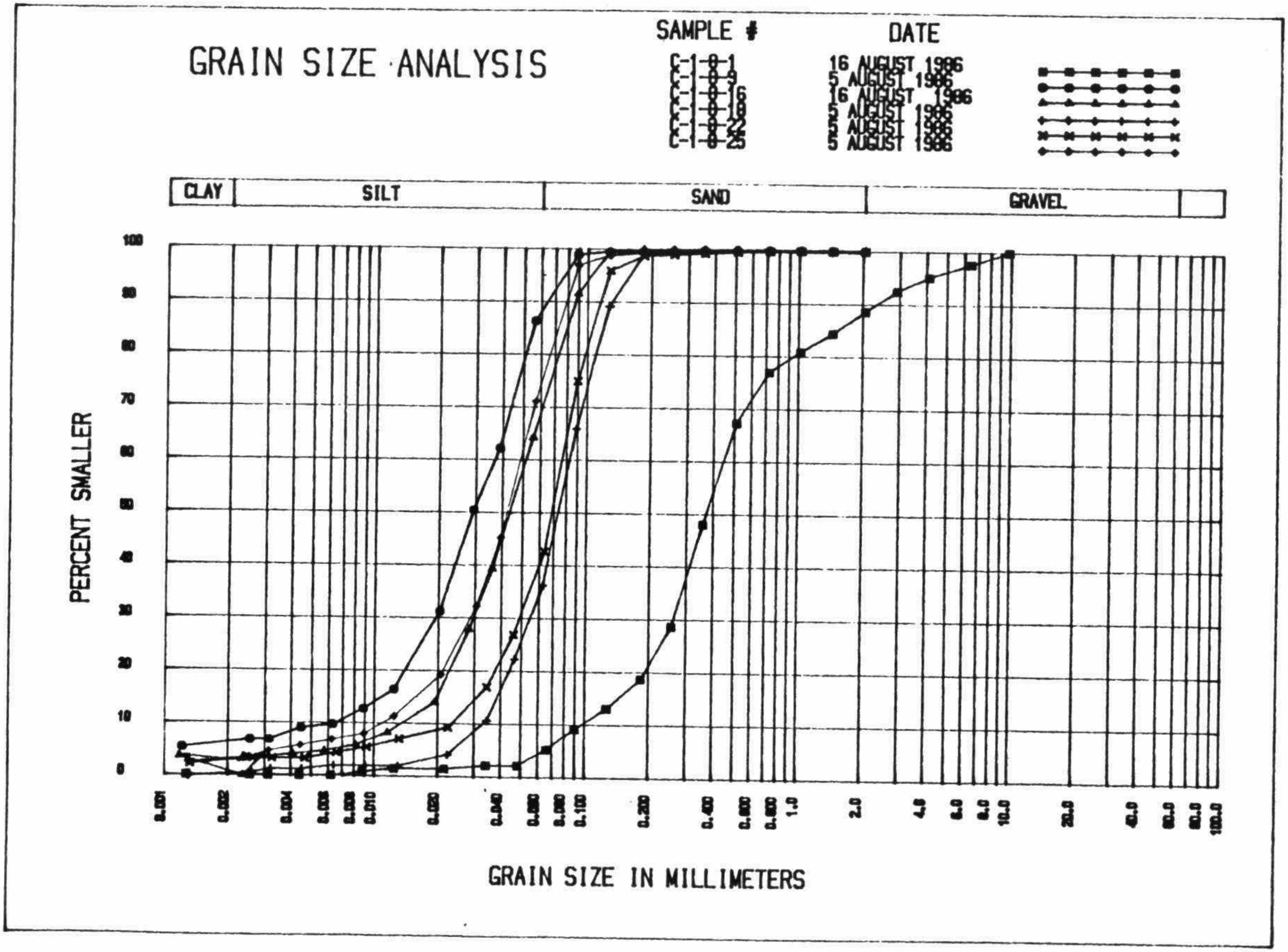
# GRAIN SIZE ANALYSIS

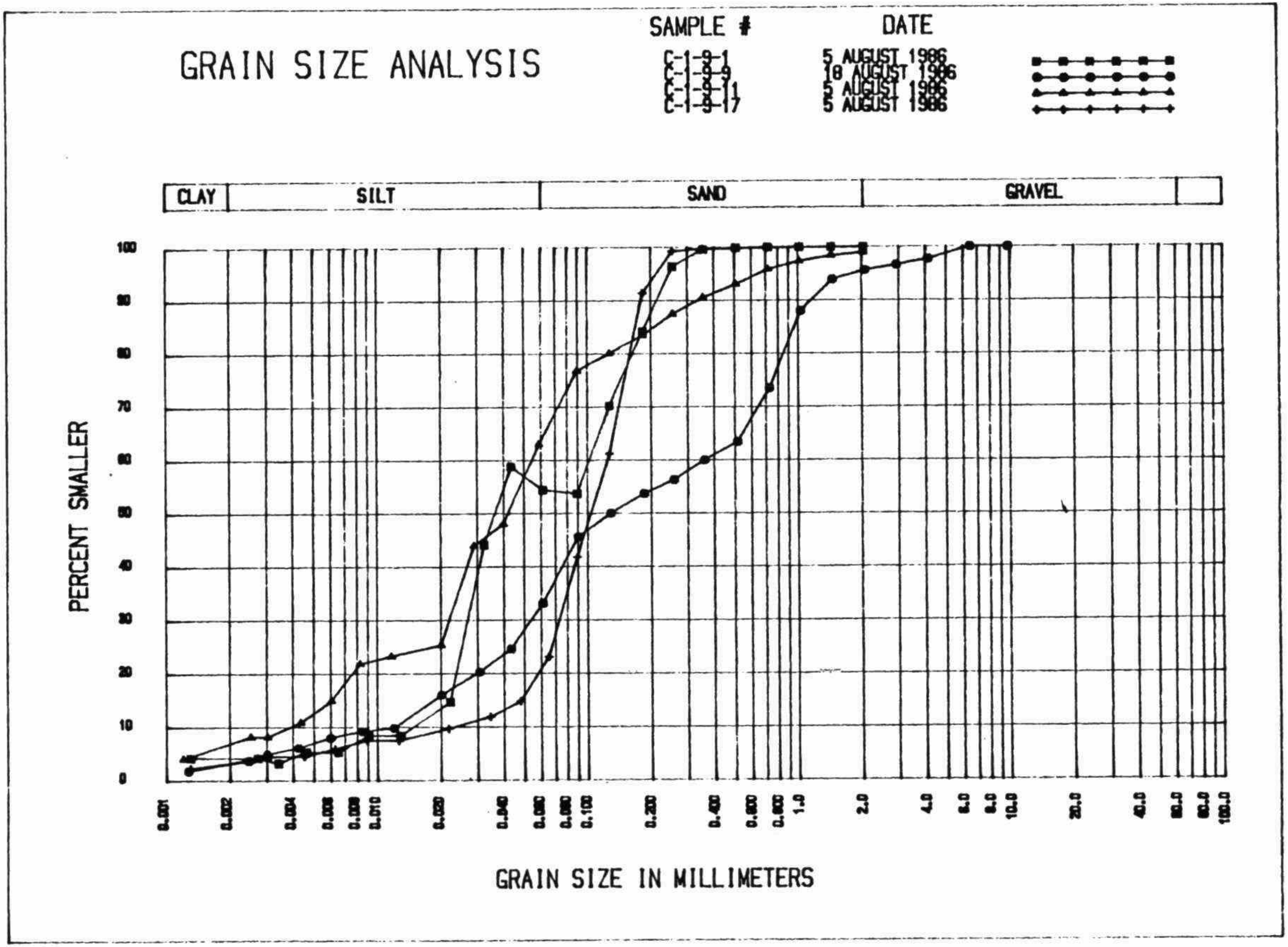
C-1-6-1

| SAMPLE # | DATE | |
|---|---|---|
| C1HH'.DAT | 14 AUGUST 1986 | ■—■—■—■—■—■ |
| C-1-6-8 | 5 AUGUST 1986 | ●—●—●—●—●—● |
| C-1-6-11 | 5 AUGUST 1986 | ▲—▲—▲—▲—▲—▲ |
| C-1-6-15 | 5 AUGUST 1986 | +—+—+—+—+—+ |
| ~~C-1-6-18~~ | 5 AUGUST 1986 | ✕—✕—✕—✕—✕—✕ |




GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-1-7-1 5 AUGUST 1986 ■
C-1-7-3 5 AUGUST 1986 ●
C-1-7-7 16 AUGUST 1986 ▲
C-1-7-12 5 AUGUST 1986 ◆
C-1-7-18 16 AUGUST 1986 ✖
C-1-7-23 16 AUGUST 1986 ◆
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
100
90
80
70
60
50
40
30
20
10
0
0.001
0.002
0.004
0.006
0.008
0.010
0.020
0.040
0.060
0.080
0.100
0.200
0.400
0.600
0.800
1.0
2.0
4.0
6.0
8.0
10.0
20.0
40.0
60.0
80.0
100.0
GRAIN SIZE IN MILLIMETERS


GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-1-0-1 16 AUGUST 1986 ■
C-1-0-9 5 AUGUST 1986 ●
C-1-0-16 16 AUGUST 1986 ▲
C-1-0-18 5 AUGUST 1986 +
C-1-0-22 5 AUGUST 1986 ×
C-1-0-25 5 AUGUST 1986 ◆
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
100
90
80
70
60
50
40
30
20
10
0
0.001
0.002
0.004
0.006
0.008
0.010
0.020
0.040
0.060
0.080
0.100
0.200
0.400
0.600
0.800
1.0
2.0
4.0
6.0
8.0
10.0
20.0
40.0
60.0
80.0
100.0
GRAIN SIZE IN MILLIMETERS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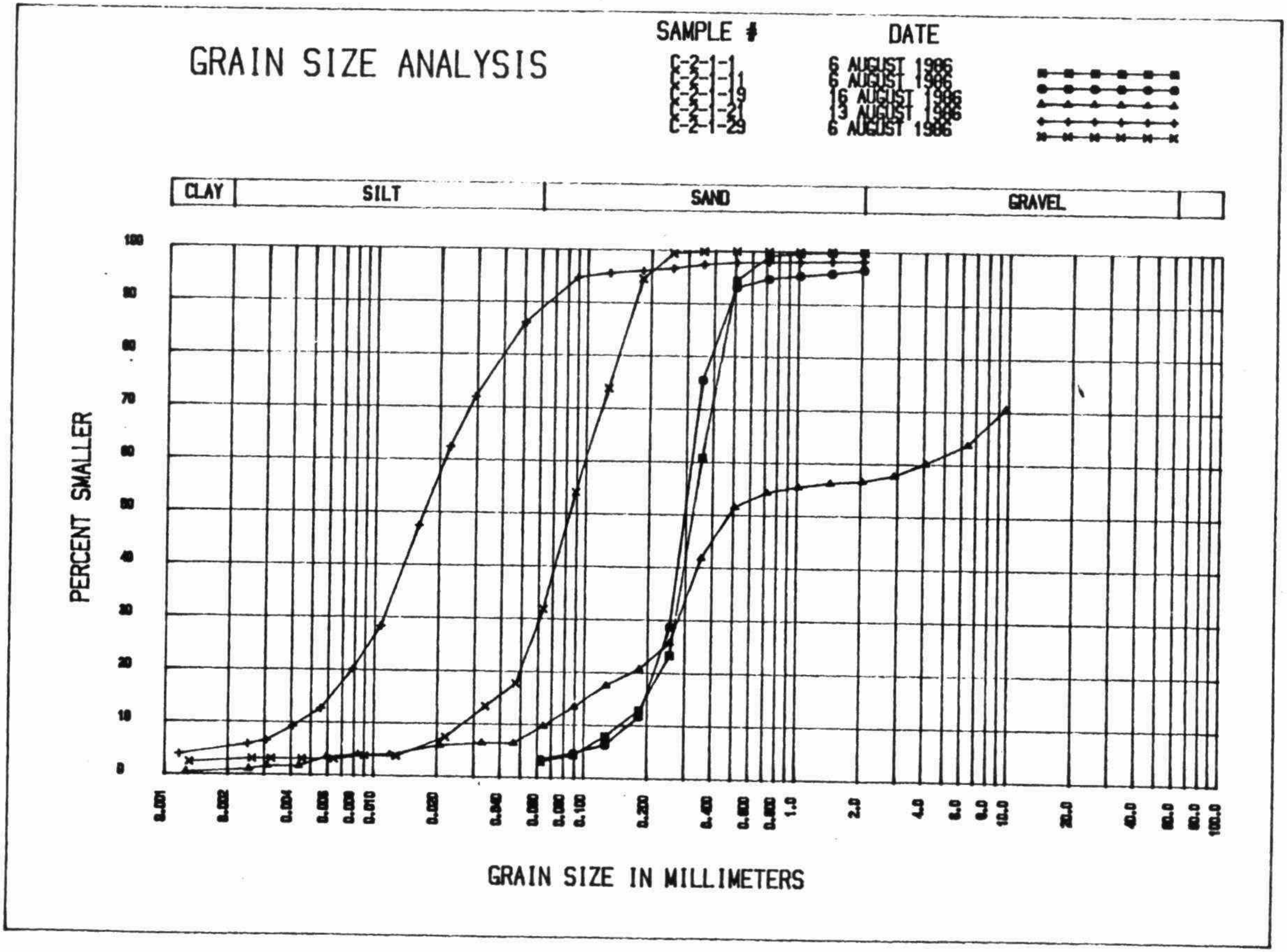
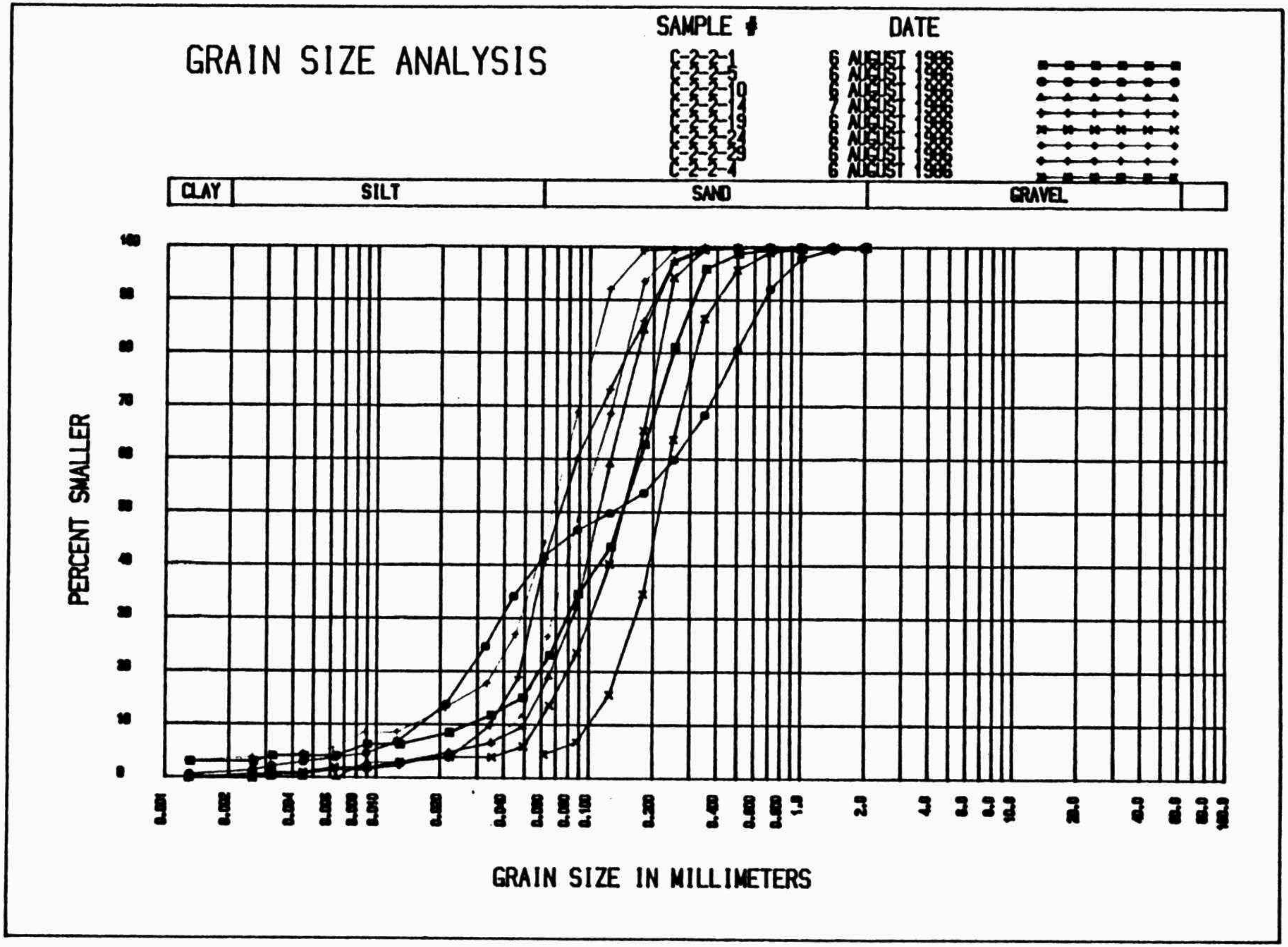
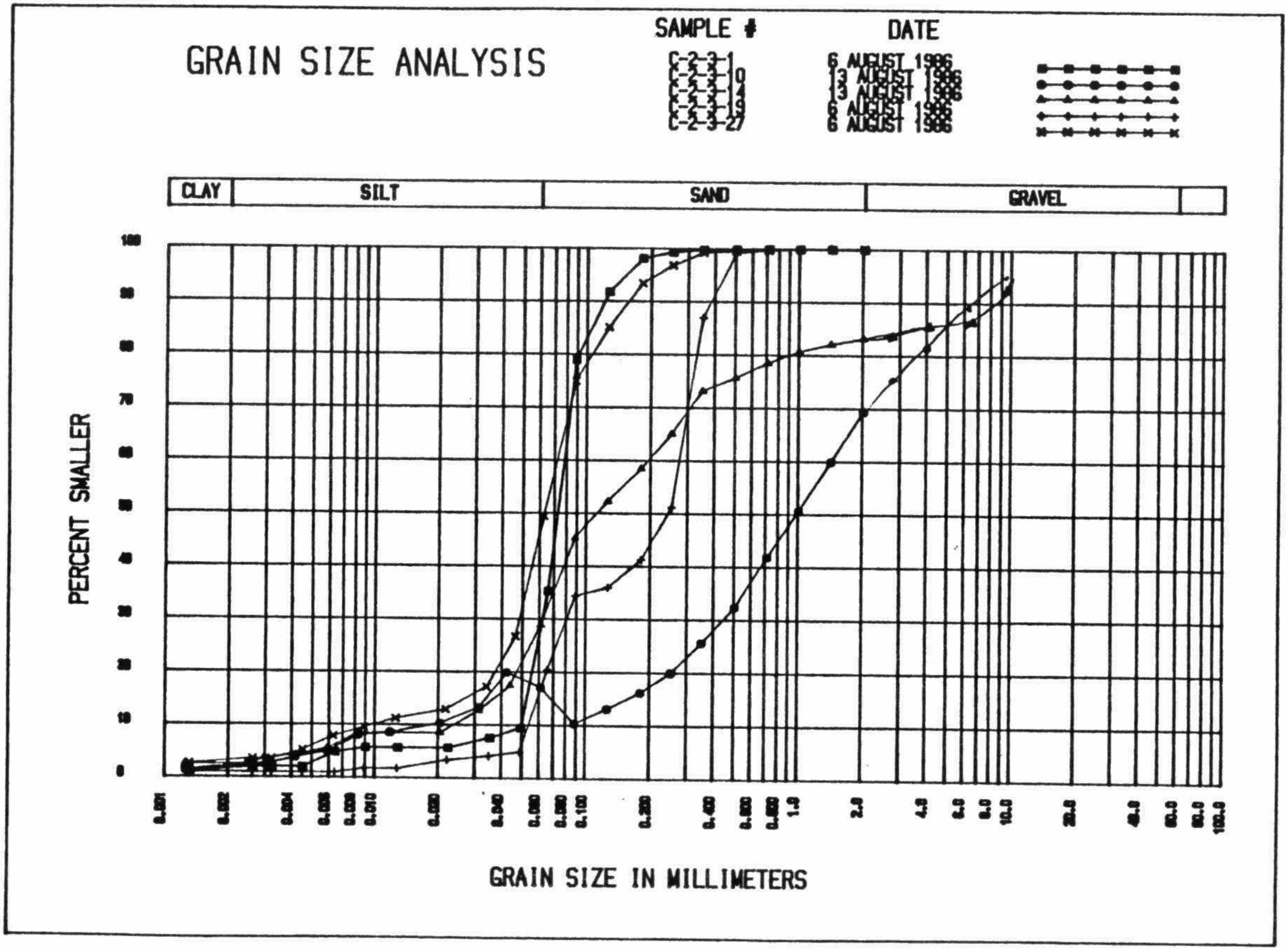
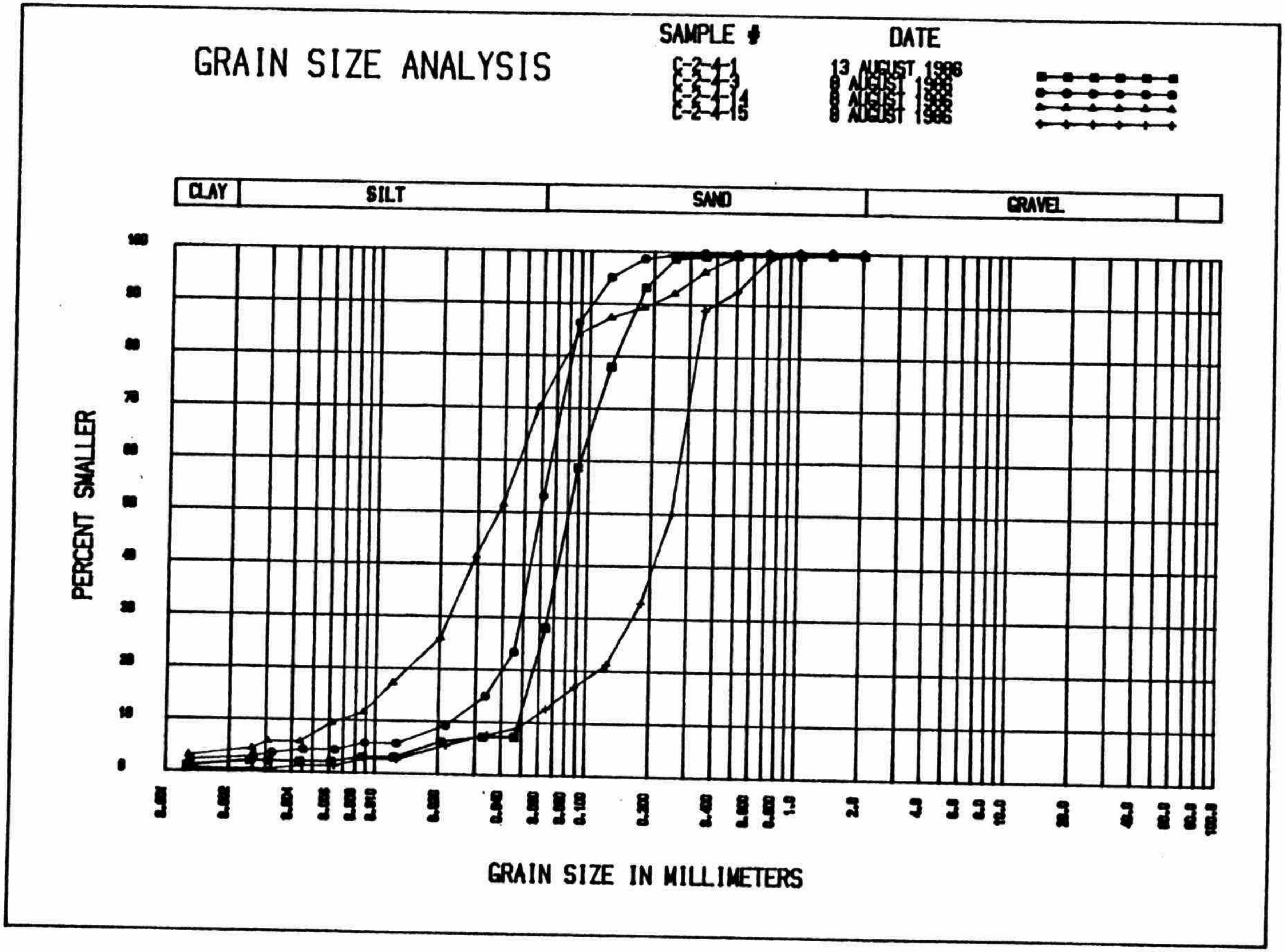
SAMPLE #
DATE
C-1-9-1 5 AUGUST 1986 ■
C-1-9-9 18 AUGUST 1986 ●
C-1-9-11 5 AUGUST 1986 ▲
C-1-9-17 5 AUGUST 1986 +
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
100
90
80
70
60
50
40
30
20
10
0
0.001
0.002
0.004
0.006
0.008
0.010
0.020
0.040
0.060
0.080
0.100
0.200
0.400
0.600
0.800
1.0
2.0
4.0
6.0
8.0
10.0
20.0
40.0
60.0
80.0
100.0
GRAIN SIZE IN MILLIMETERS


GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-2-1-1 6 AUGUST 1986 ■
C-2-1-11 6 AUGUST 1986 ●
C-2-1-19 16 AUGUST 1986 ▲
C-2-1-21 13 AUGUST 1986 ◆
C-2-1-29 6 AUGUST 1986 ✕
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
0
10
20
30
40
50
60
70
80
90
100
0.001
0.002
0.004
0.006
0.008
0.010
0.020
0.040
0.060
0.080
0.100
0.200
0.400
0.600
0.800
1.0
2.0
4.0
6.0
8.0
10.0
20.0
40.0
60.0
80.0
100.0
GRAIN SIZE IN MILLIMETERS


GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-2-2-1 6 AUGUST 1986
C-2-2-5 6 AUGUST 1986
C-2-2-10 6 AUGUST 1986
C-2-2-14 7 AUGUST 1986
C-2-2-19 6 AUGUST 1986
C-2-2-24 6 AUGUST 1986
C-2-2-23 6 AUGUST 1986
C-2-2-4 6 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
100
90
80
70
60
50
40
30
20
10
0
0.001
0.002
0.004
0.006
0.008
0.010
0.020
0.040
0.060
0.080
0.100
0.200
0.400
0.600
0.800
1.0
2.0
4.0
6.0
8.0
10.0
20.0
40.0
60.0
80.0
100.0
GRAIN SIZE IN MILLIMETERS


GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-2-3-1 6 AUGUST 1986
C-2-3-10 13 AUGUST 1986
C-2-3-14 13 AUGUST 1986
C-2-3-19 6 AUGUST 1986
C-2-3-27 6 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
100
90
80
70
60
50
40
30
20
10
0
0.001
0.002
0.004
0.006
0.008
0.010
0.020
0.040
0.060
0.080
0.100
0.200
0.400
0.600
0.800
1.0
2.0
4.0
6.0
8.0
10.0
20.0
40.0
60.0
80.0
100.0
GRAIN SIZE IN MILLIMETERS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SAMPLE #
DATE
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13 AUGUST 1986
C-2-4-3
8 AUGUST 1986
C-2-4-14
8 AUGUST 1986
C-2-4-15
8 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
100
90
80
70
60
50
40
30
20
10
0
0.001
0.002
0.004
0.006
0.008
0.010
0.020
0.040
0.060
0.080
0.100
0.200
0.400
0.600
0.800
1.0
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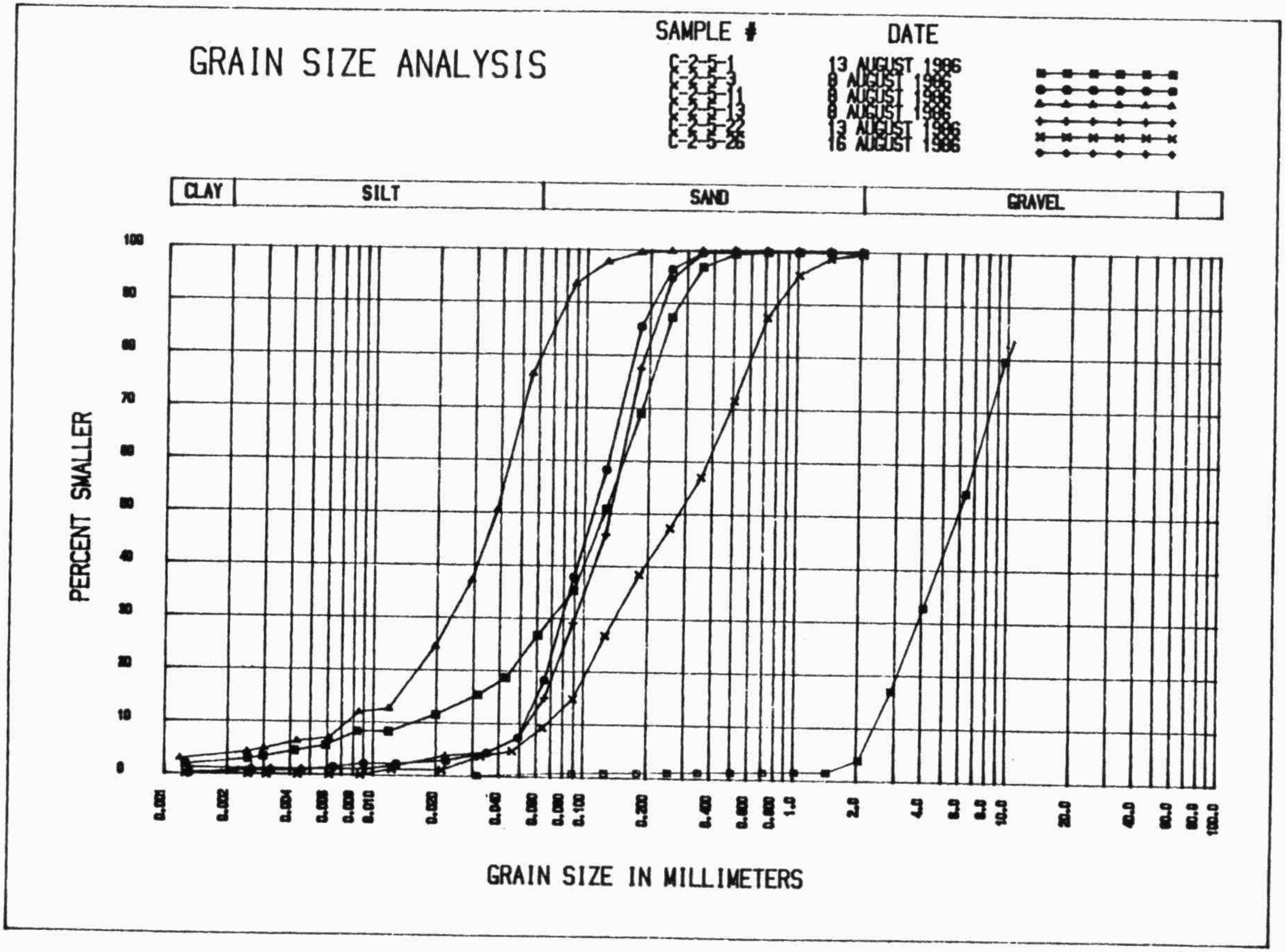
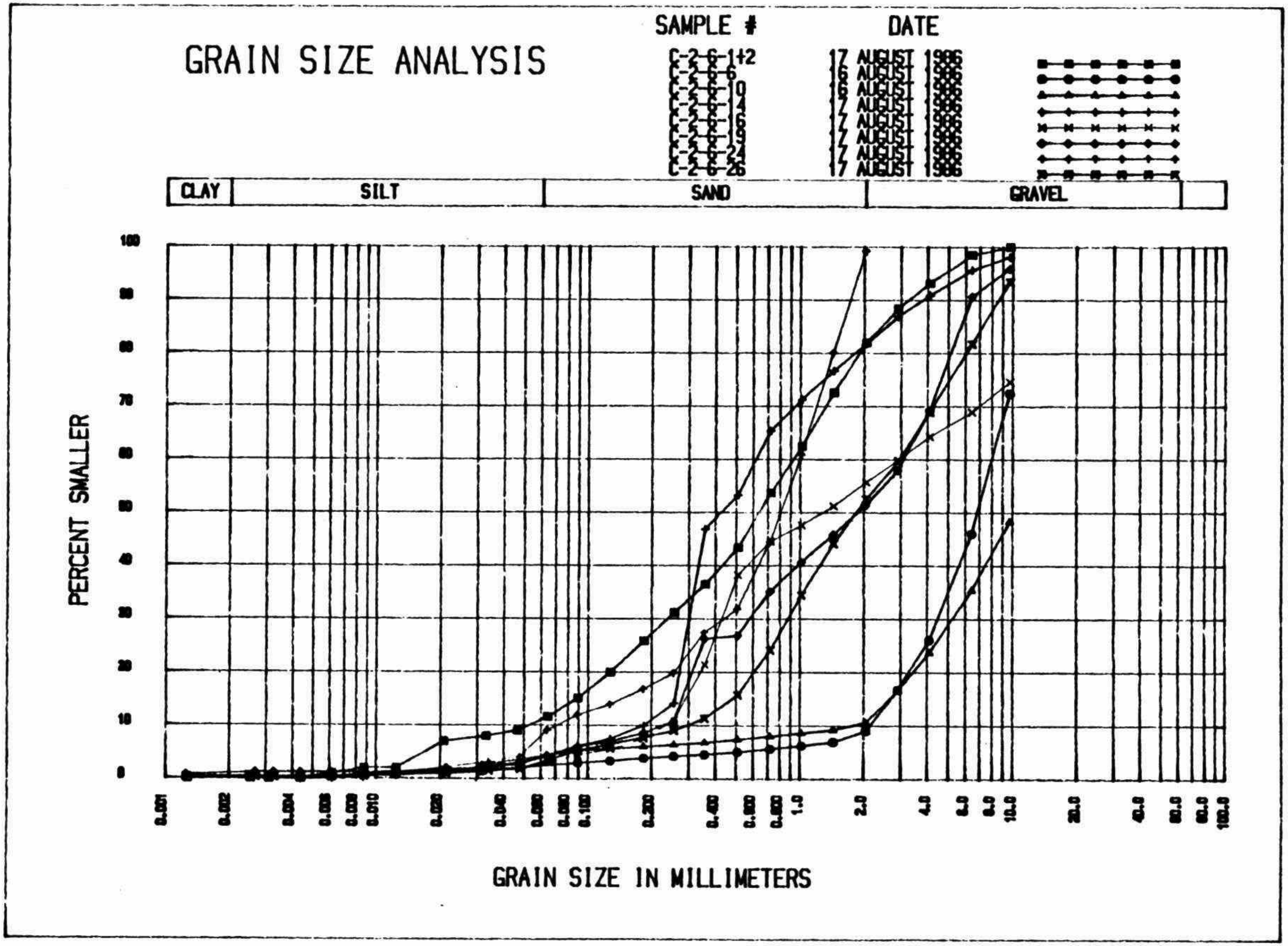
80.0
100.0
GRAIN SIZE IN MILLIMETERS



GRAIN SIZE ANALYSIS


GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-2-6-1+2 17 AUGUST 1986 ■
C-2-6-6 16 AUGUST 1986 ●
C-2-6-10 16 AUGUST 1986 ▲
C-2-6-14 17 AUGUST 1986 ◆
C-2-6-16 17 AUGUST 1986 ×
C-2-6-19 17 AUGUST 1986 ◆
C-2-6-24 17 AUGUST 1986 ◆
C-2-6-26 17 AUGUST 1986 ■
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
100
90
80
70
60
50
40
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0.001
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0.006
0.008
0.010
0.020
0.040
0.060
0.080
0.100
0.200
0.400
0.600
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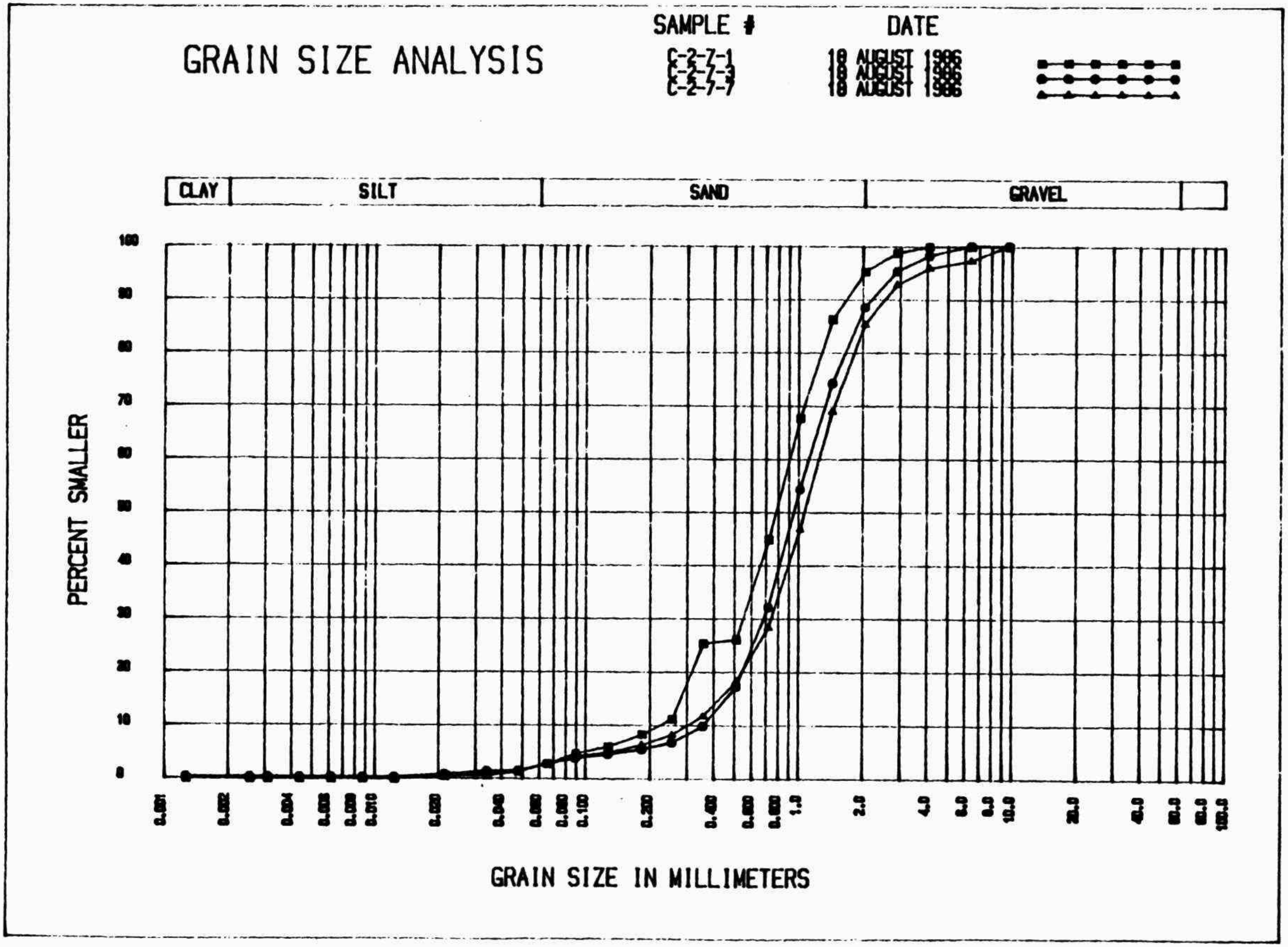
GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-2-7-1 18 AUGUST 1986 ■
C-2-7-3 18 AUGUST 1986 ●
C-2-7-7 18 AUGUST 1986 ▲
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
100
90
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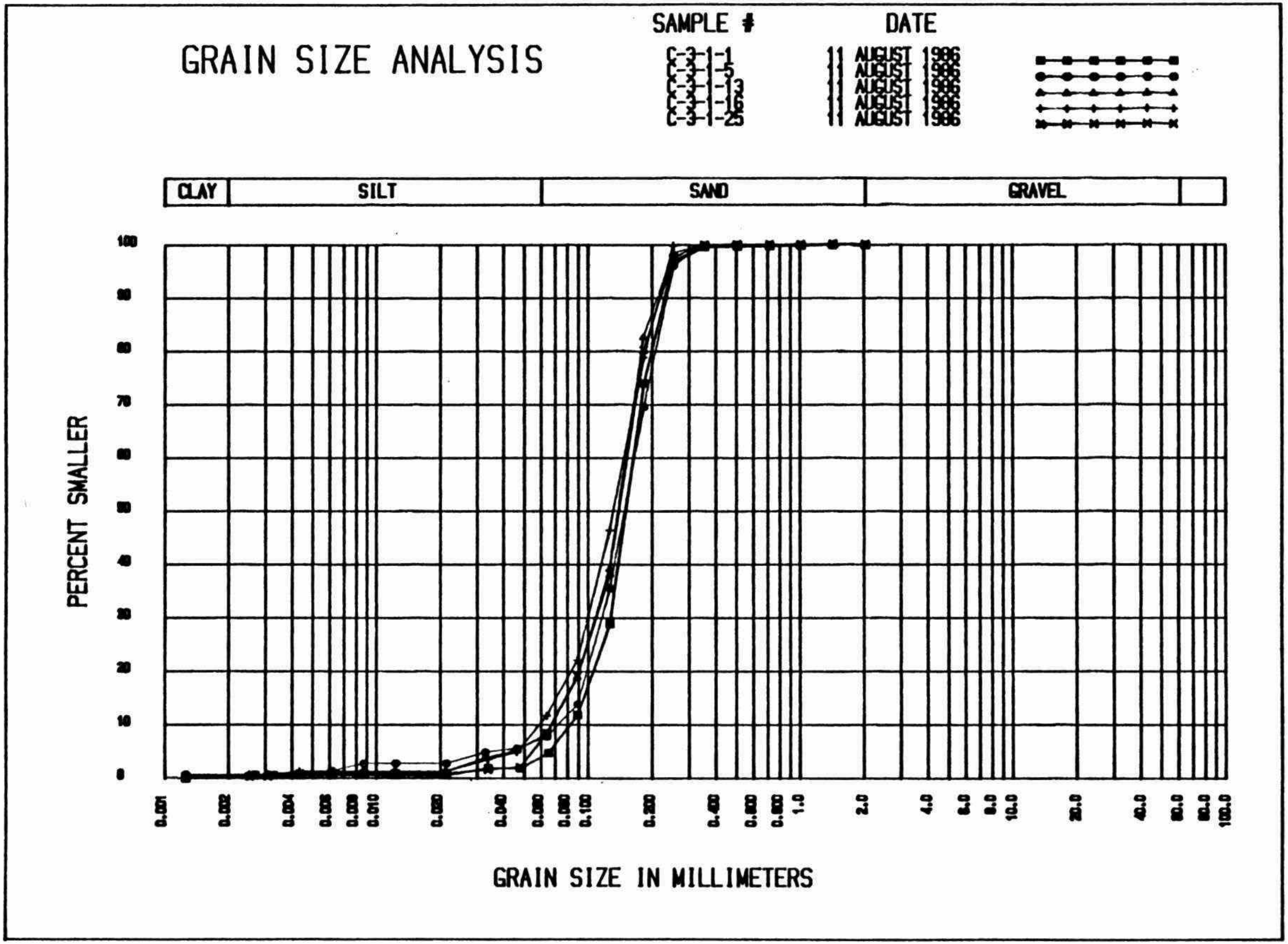
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SAMPLE #
DATE
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C-3-1-5 11 AUGUST 1986
C-3-1-13 11 AUGUST 1986
C-3-1-16 11 AUGUST 1986
C-3-1-25 11 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
100
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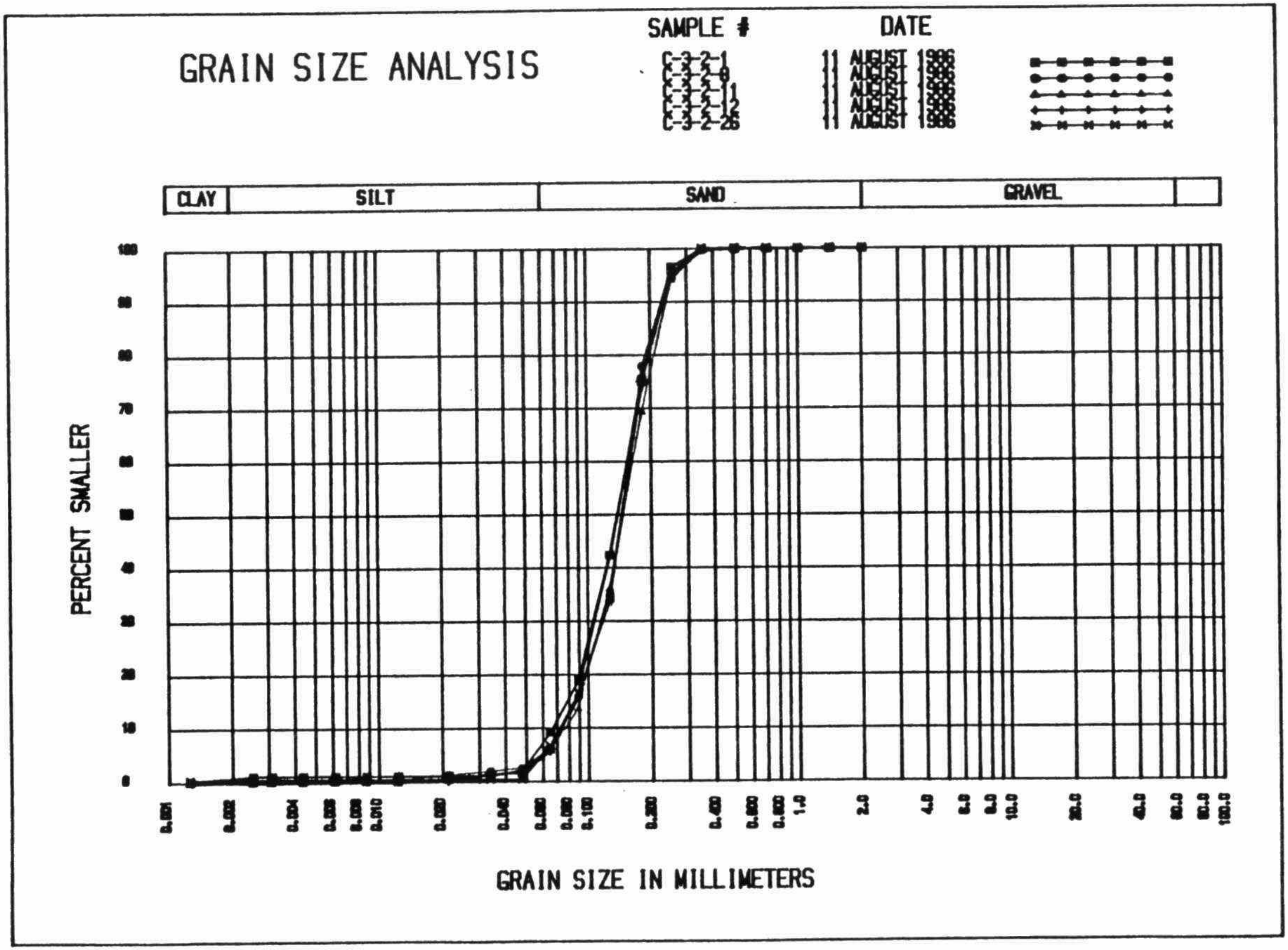
GRAIN SIZE IN MILLIMETERS

GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-3-2-1
C-3-2-8
C-3-2-11
C-3-2-12
C-3-2-26
11 AUGUST 1986
11 AUGUST 1986
11 AUGUST 1986
11 AUGUST 1986
11 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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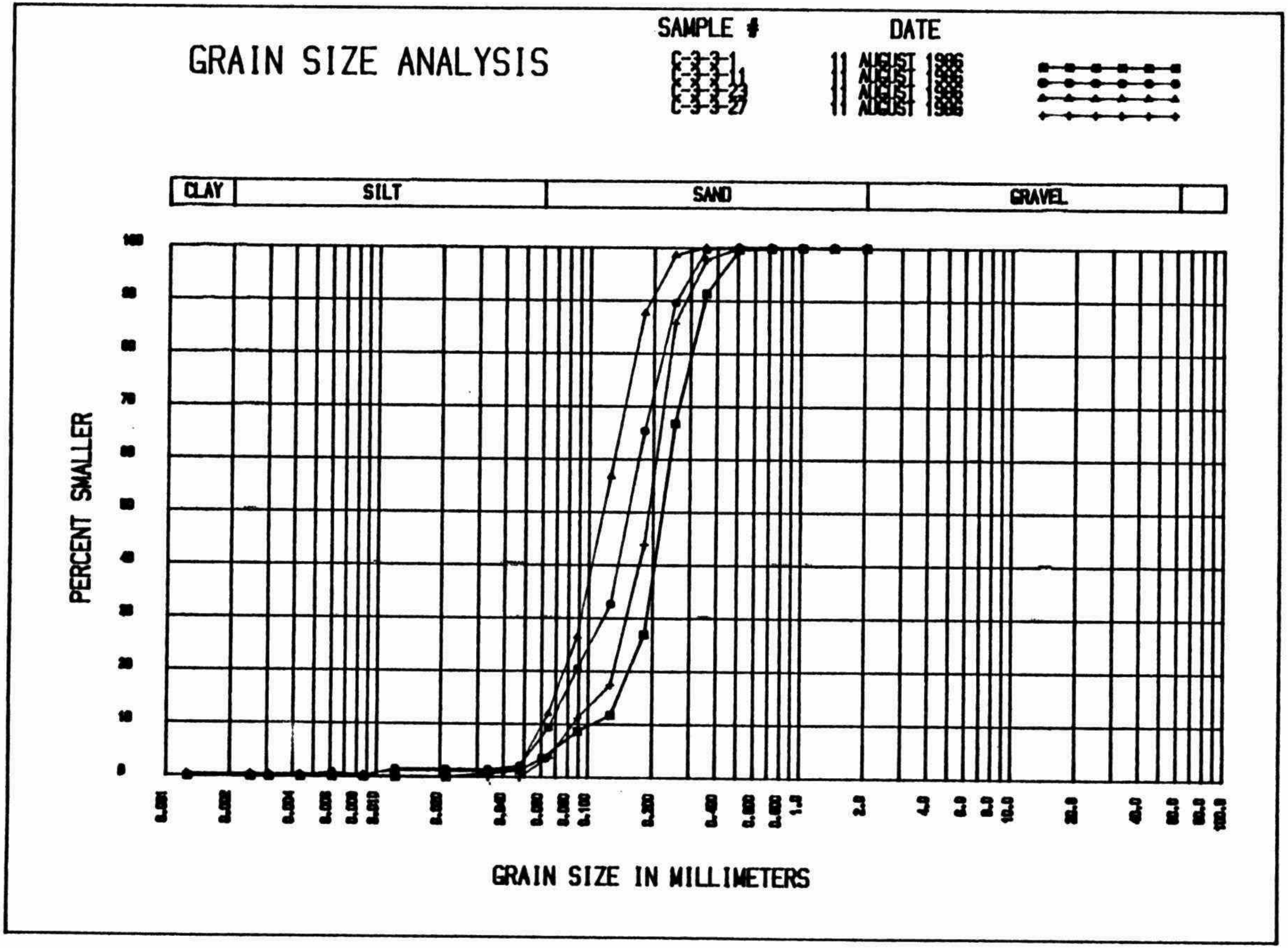
GRAIN SIZE IN MILLIMETERS


GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-3-3-1 11 AUGUST 1986 ■
C-3-3-11 11 AUGUST 1986 ●
C-3-3-23 11 AUGUST 1986 ▲
C-3-3-27 11 AUGUST 1986 ◆
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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0.006
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0.040
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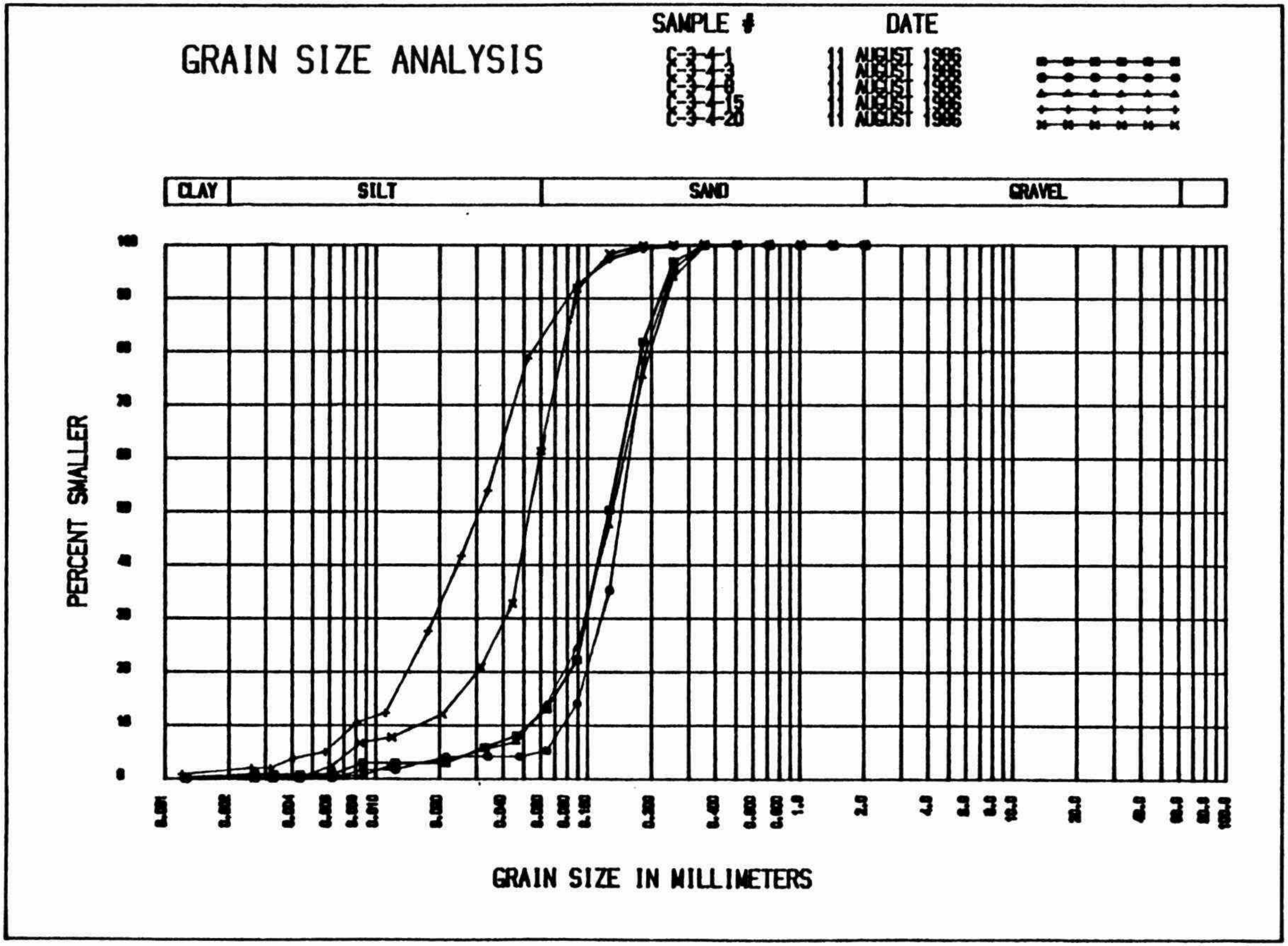
GRAIN SIZE IN MILLIMETERS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SAMPLE #
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C-3-4-1
C-3-4-3
C-3-4-8
C-3-4-15
C-3-4-20
11 AUGUST 1986
11 AUGUST 1986
11 AUGUST 1986
11 AUGUST 1986
11 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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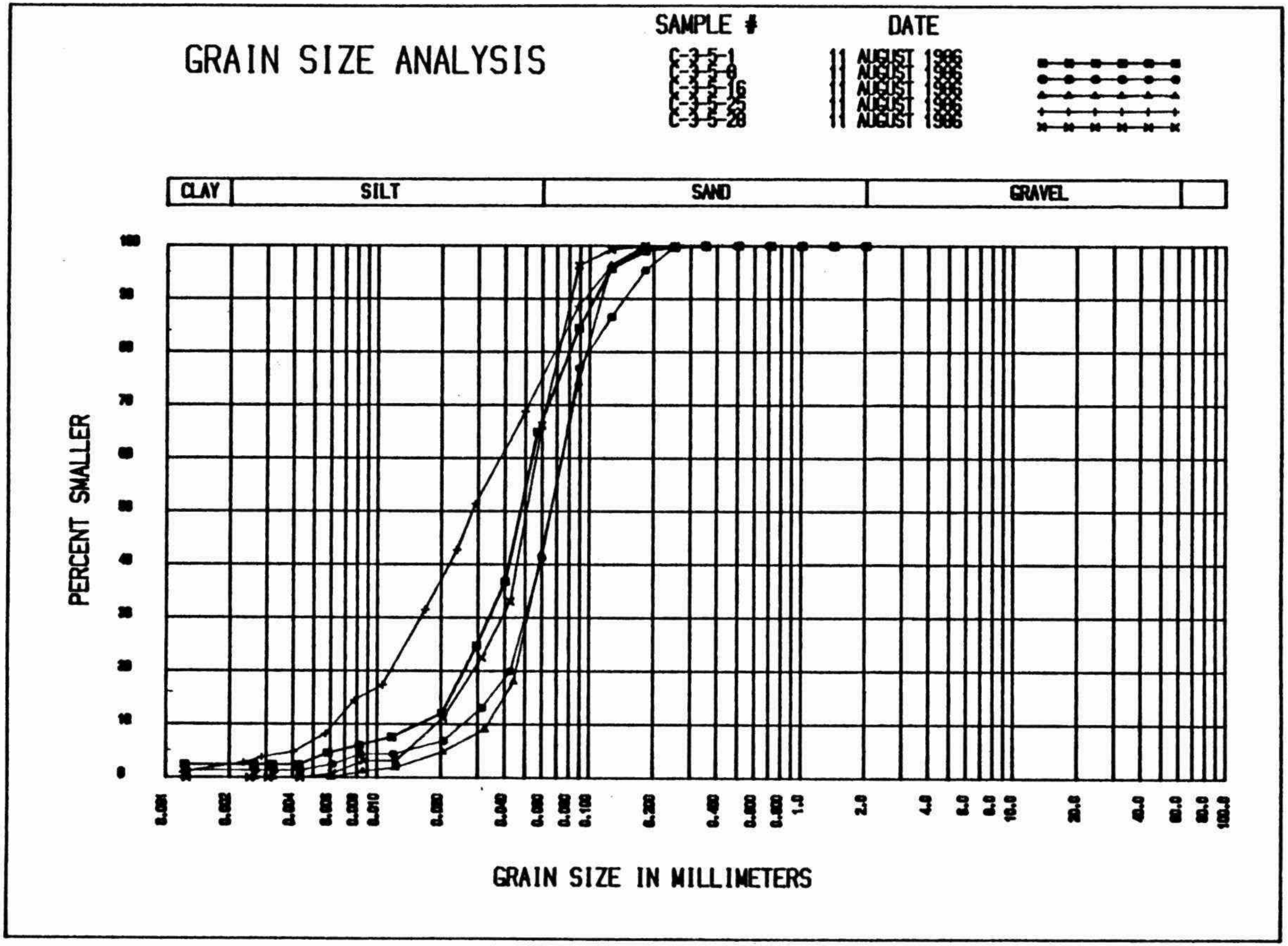
GRAIN SIZE IN MILLIMETERS


GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-3-5-1
C-3-5-8
C-3-5-16
C-3-5-25
C-3-5-28
11 AUGUST 1986
11 AUGUST 1986
11 AUGUST 1986
11 AUGUST 1986
11 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
100
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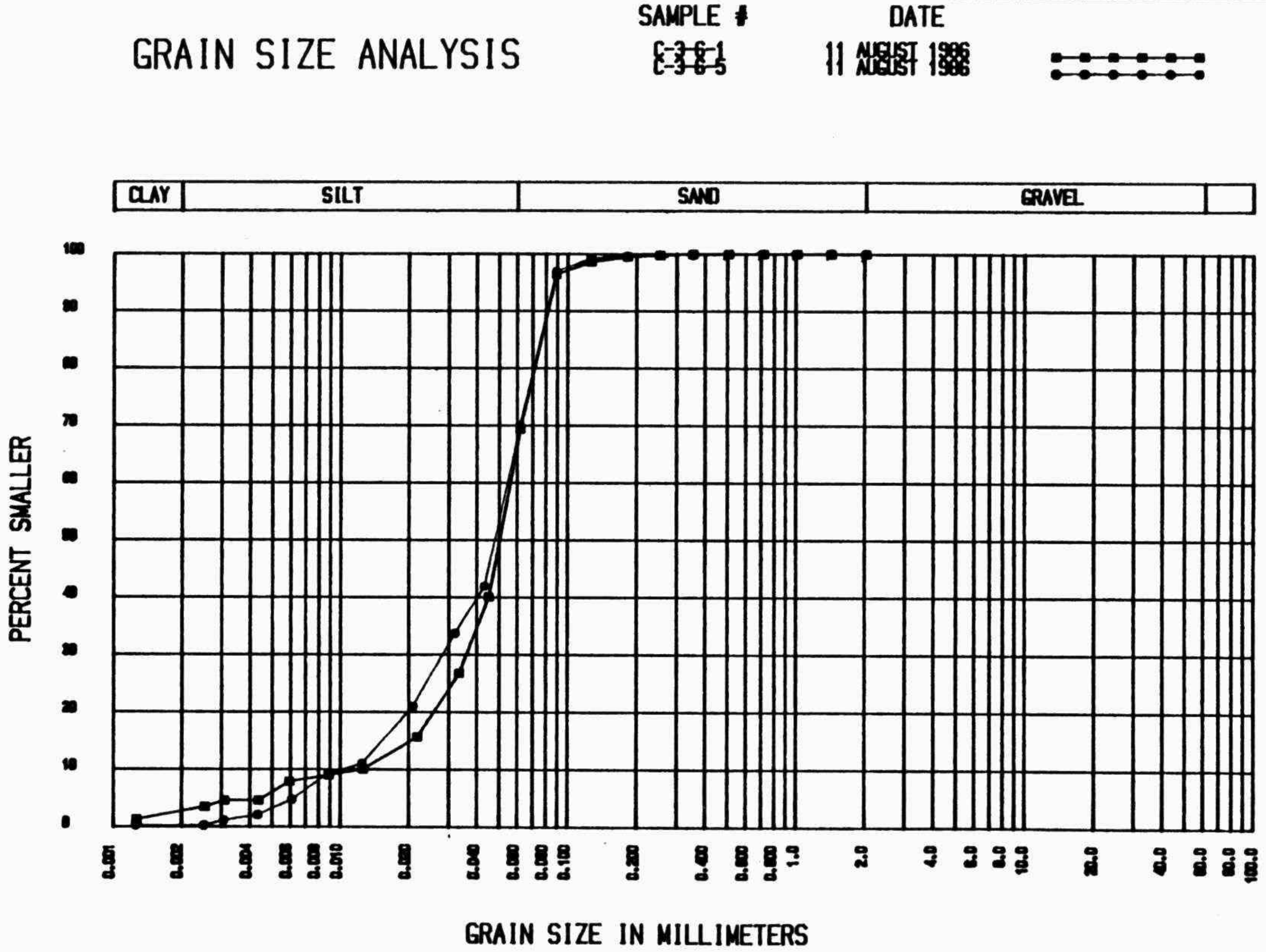
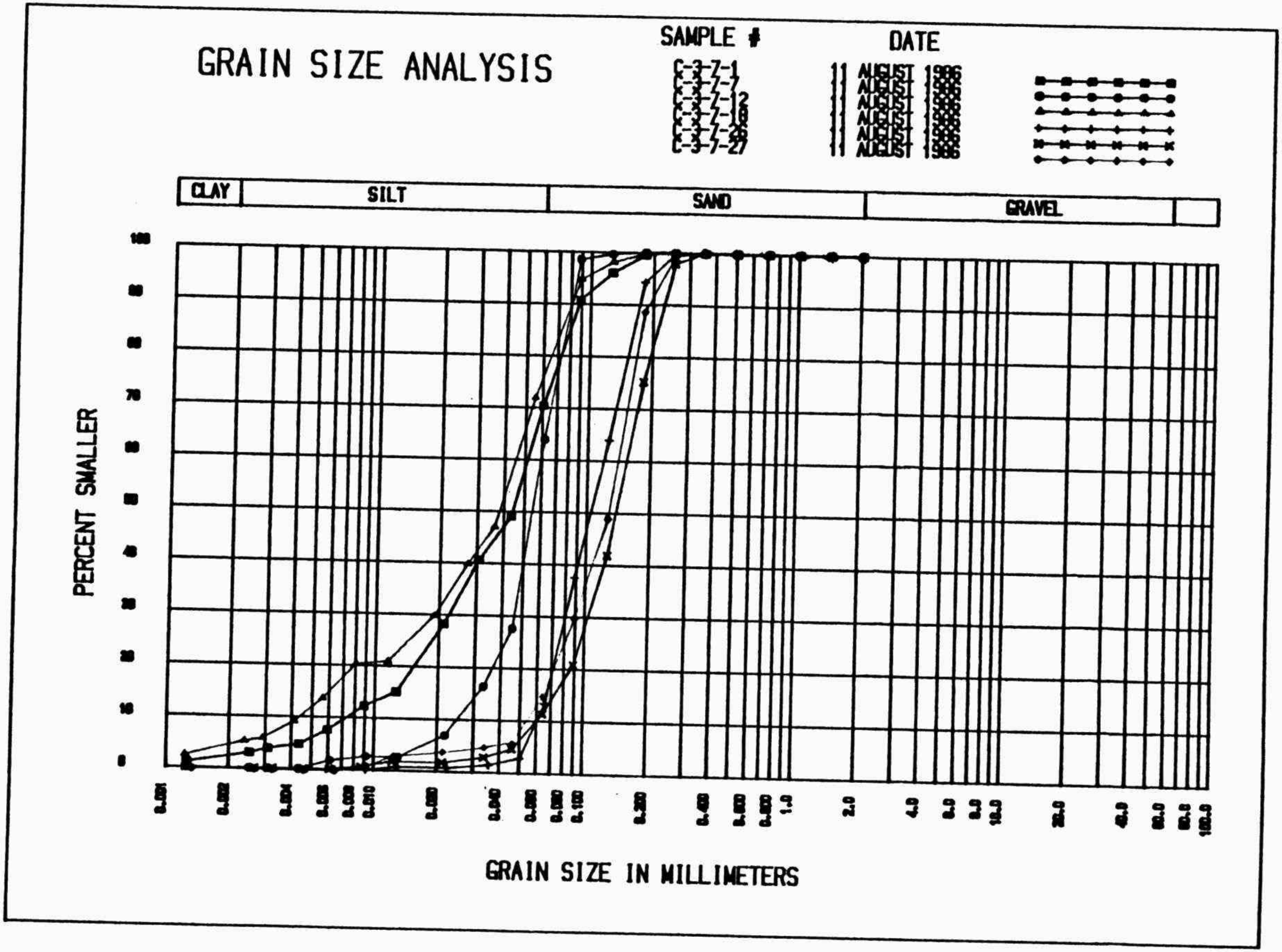
100.0
GRAIN SIZE IN MILLIMETERS

# GRAIN SIZE ANALYSIS




GRAIN SIZE ANALYSIS
SAMPLE #
DATE
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C-3-7-7 11 AUGUST 1986 ●
C-3-7-12 11 AUGUST 1986 ▲
C-3-7-18 11 AUGUST 1986 +
C-3-7-26 11 AUGUST 1986 ✕
C-3-7-27 11 AUGUST 1986 ◆
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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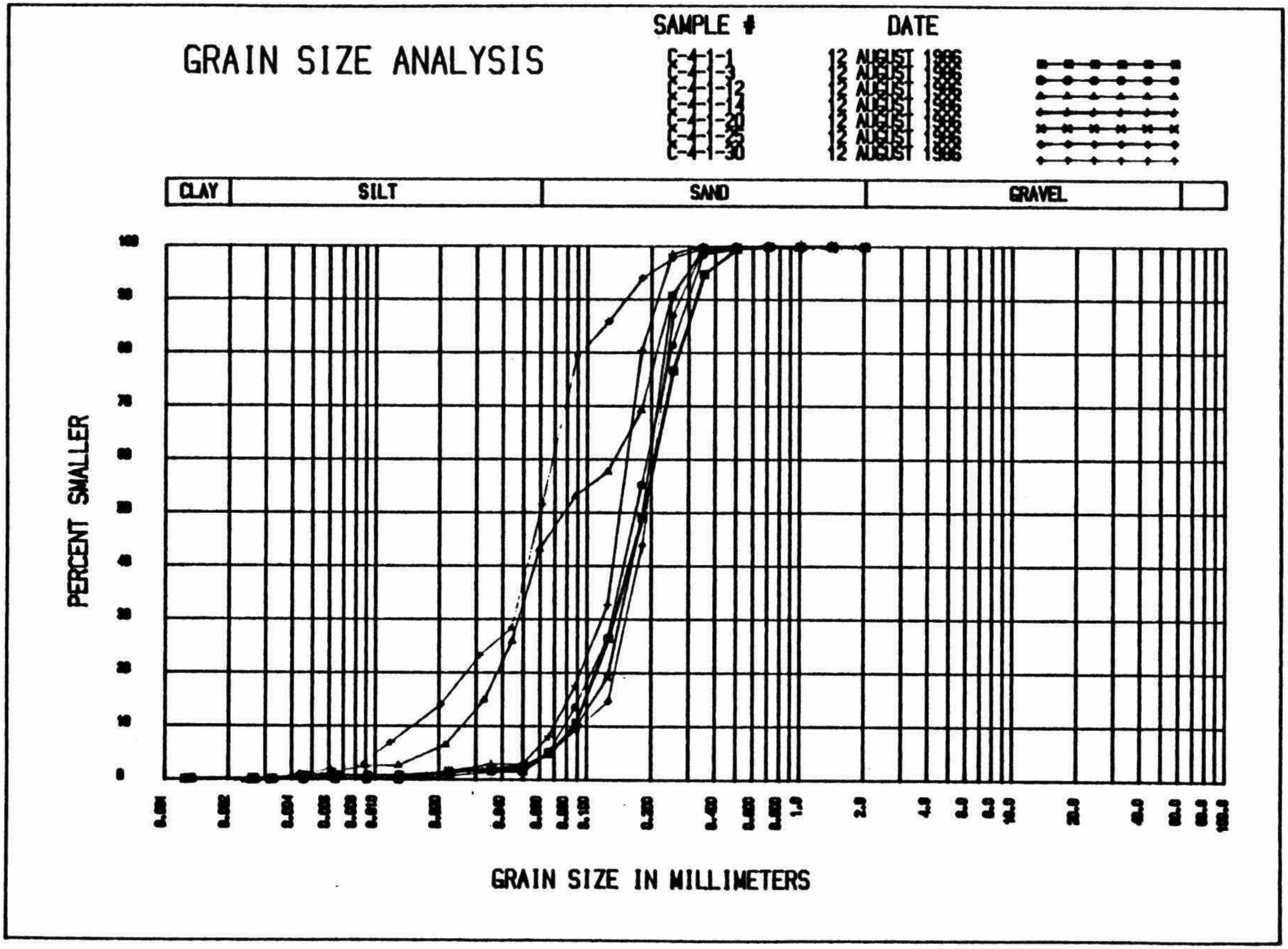
GRAIN SIZE IN MILLIMETERS


GRAIN SIZE ANALYSIS
SAMPLE #
DATE
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C-4-1-3
C-4-1-12
C-4-1-14
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C-4-1-25
C-4-1-30
12 AUGUST 1986
12 AUGUST 1986
12 AUGUST 1986
12 AUGUST 1986
12 AUGUST 1986
12 AUGUST 1986
12 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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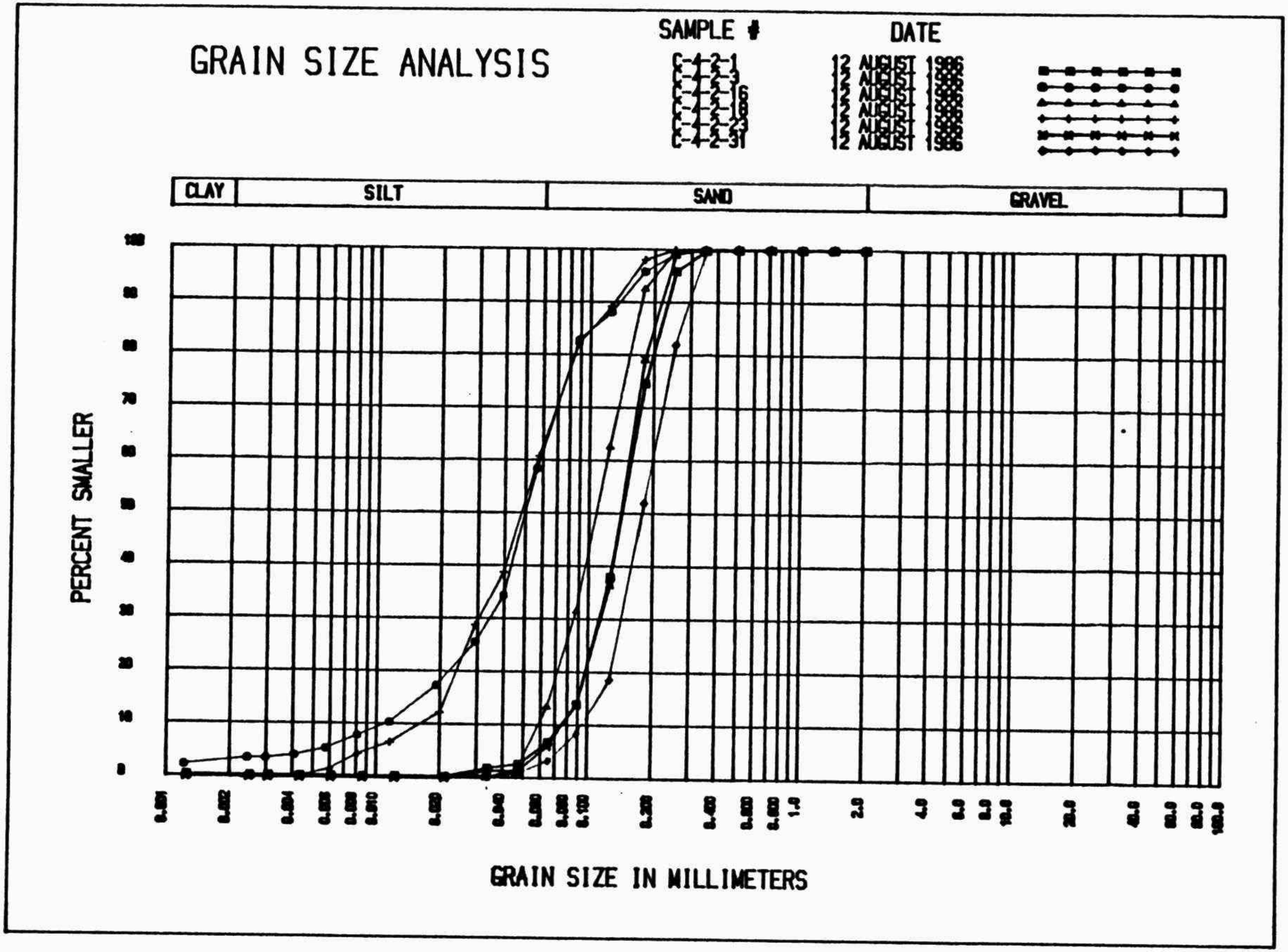
GRAIN SIZE IN MILLIMETERS


GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-4-2-1
C-4-2-3
C-4-2-16
C-4-2-18
C-4-2-23
C-4-2-31
12 AUGUST 1986
12 AUGUST 1986
12 AUGUST 1986
12 AUGUST 1986
12 AUGUST 1986
12 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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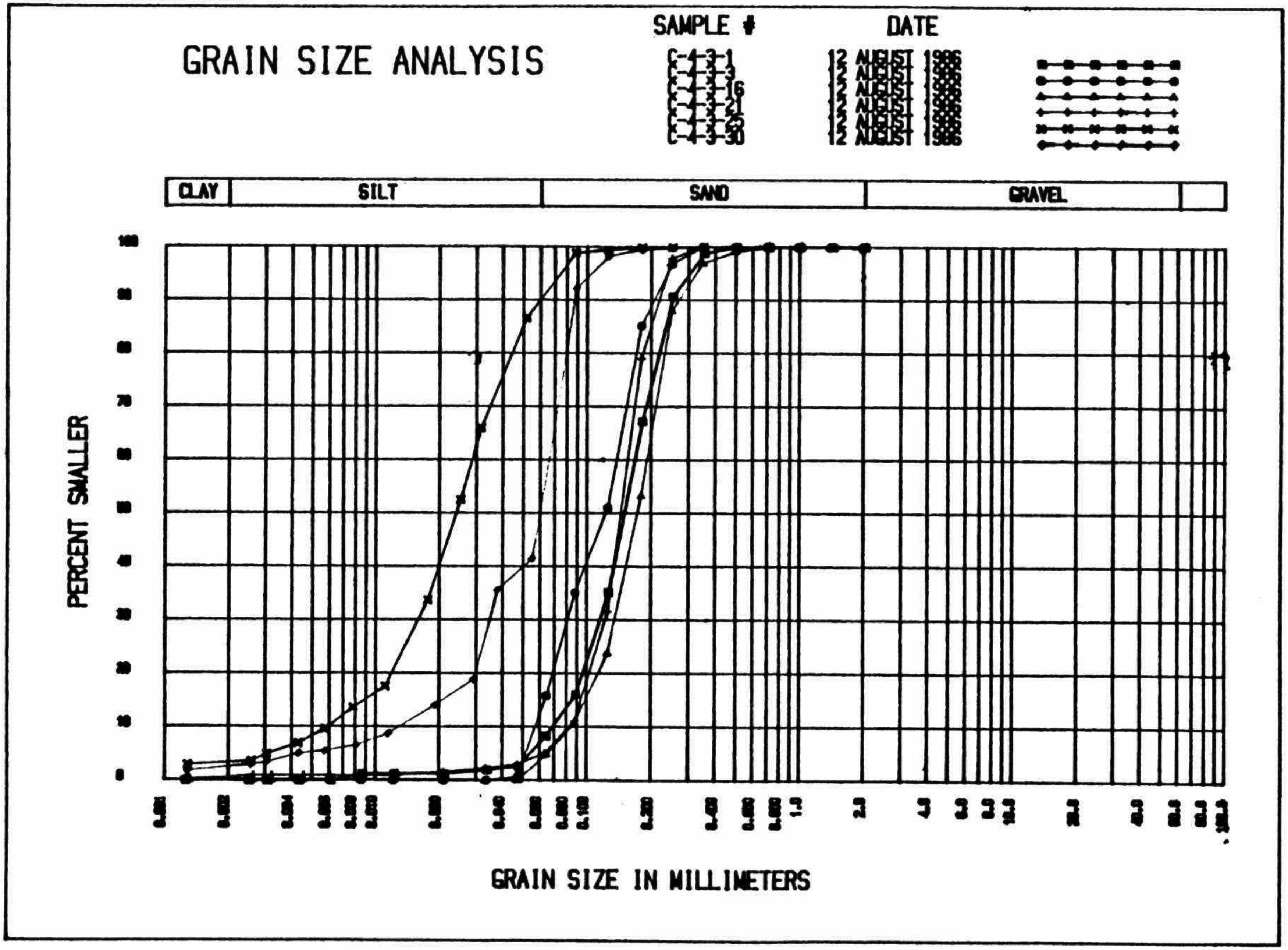
GRAIN SIZE IN MILLIMETERS

GRAIN SIZE ANALYSIS
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DATE
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C-4-3-16
C-4-3-21
C-4-3-25
C-4-3-30
12 AUGUST 1986
12 AUGUST 1986
12 AUGUST 1986
12 AUGUST 1986
12 AUGUST 1986
12 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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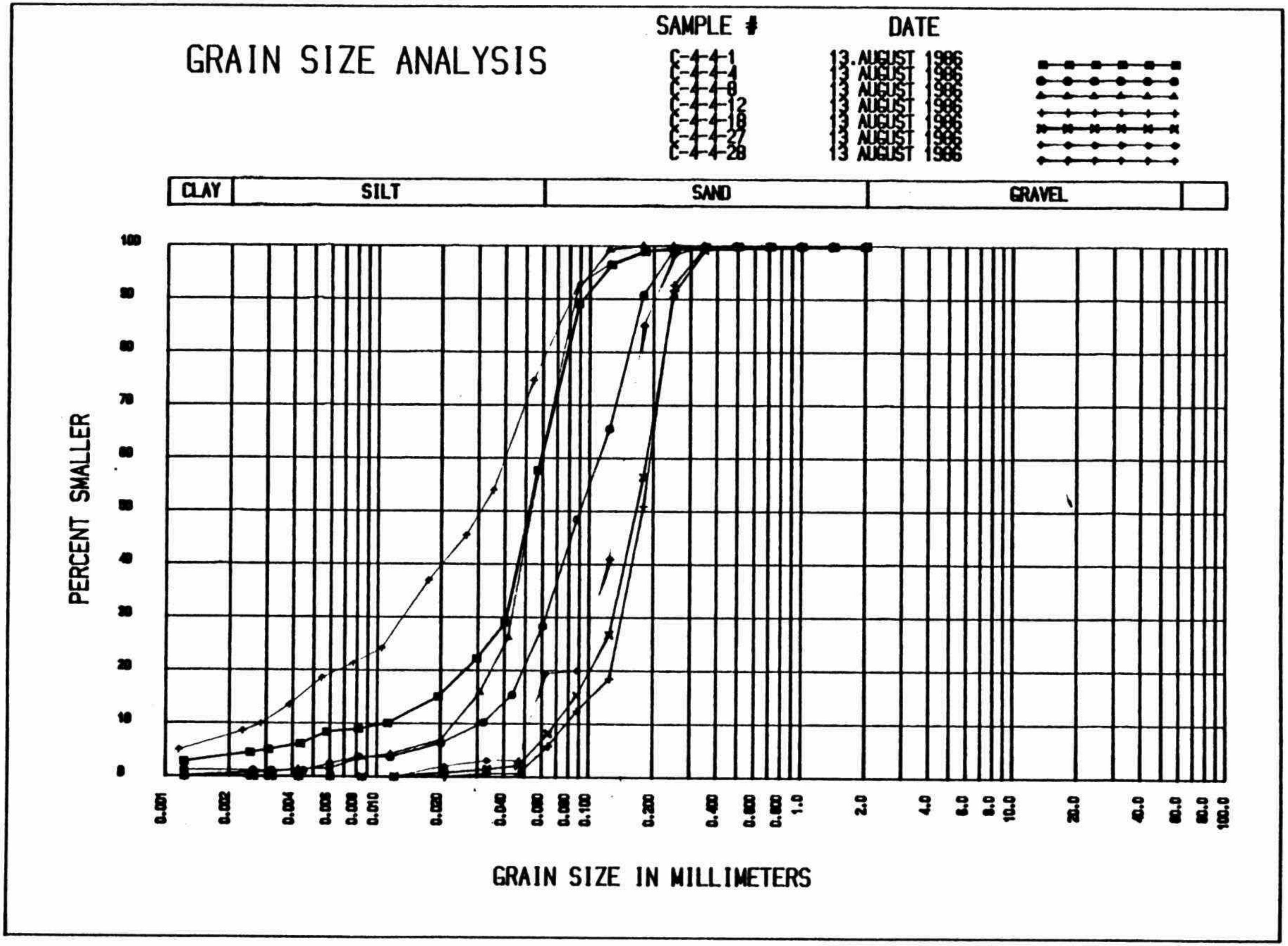
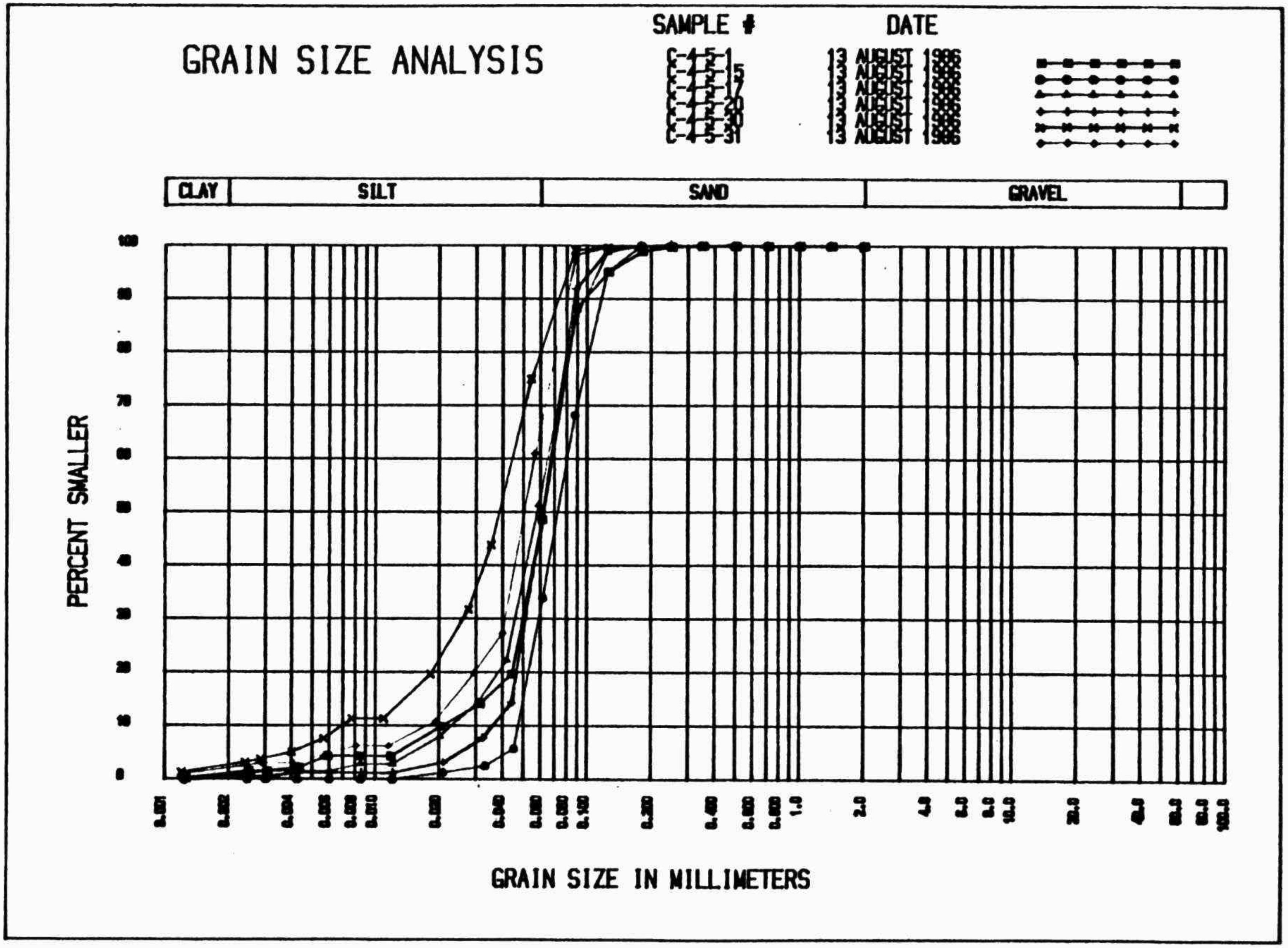
GRAIN SIZE IN MILLIMETERS


GRAIN SIZE ANALYSIS


GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-4-5-1
C-4-5-15
C-4-5-17
C-4-5-20
C-4-5-30
C-4-5-31
13 AUGUST 1986
13 AUGUST 1986
13 AUGUST 1986
13 AUGUST 1986
13 AUGUST 1986
13 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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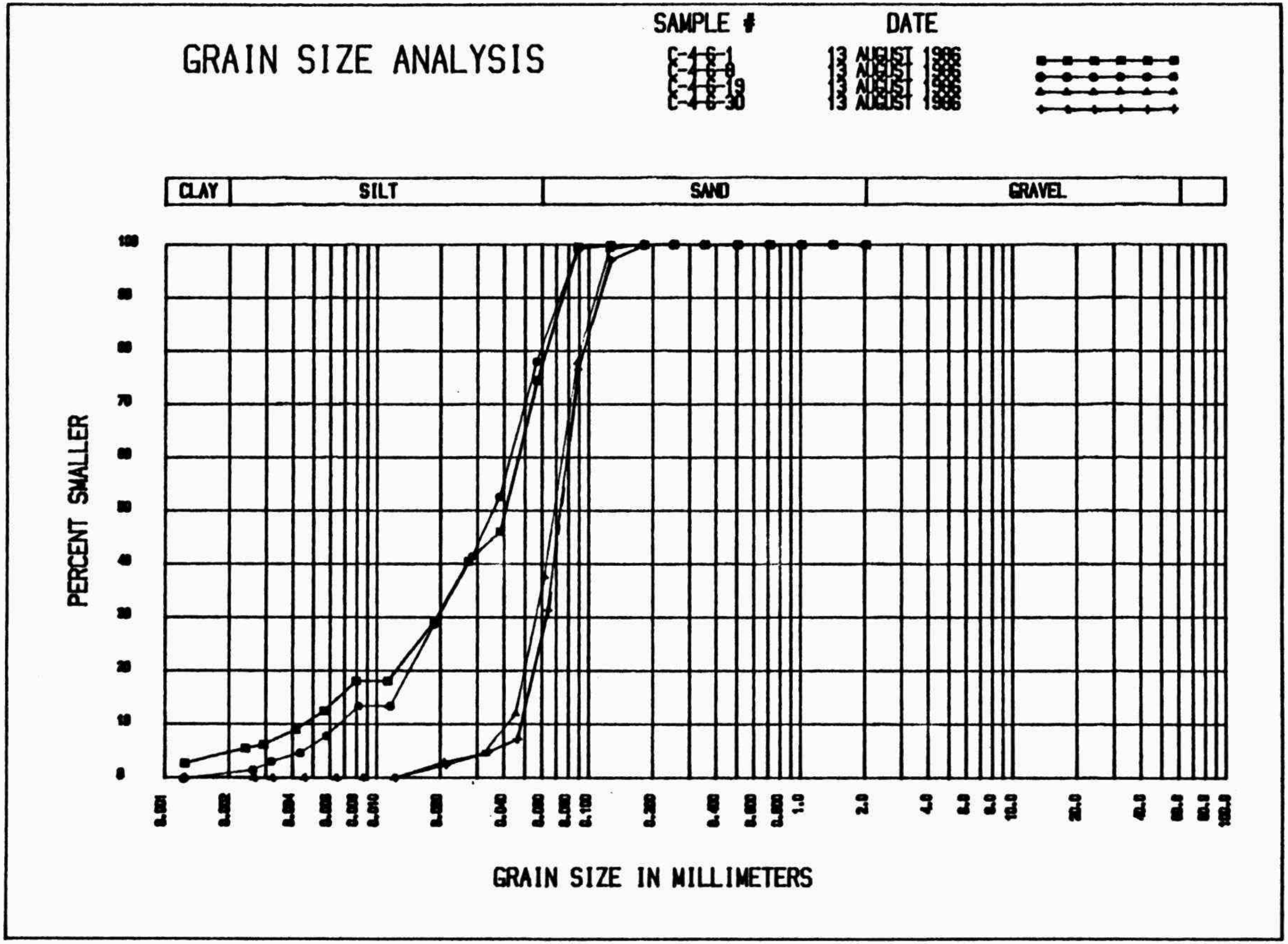
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SAMPLE #
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C-4-6-8 13 AUGUST 1986
C-4-6-19 13 AUGUST 1986
C-4-6-30 13 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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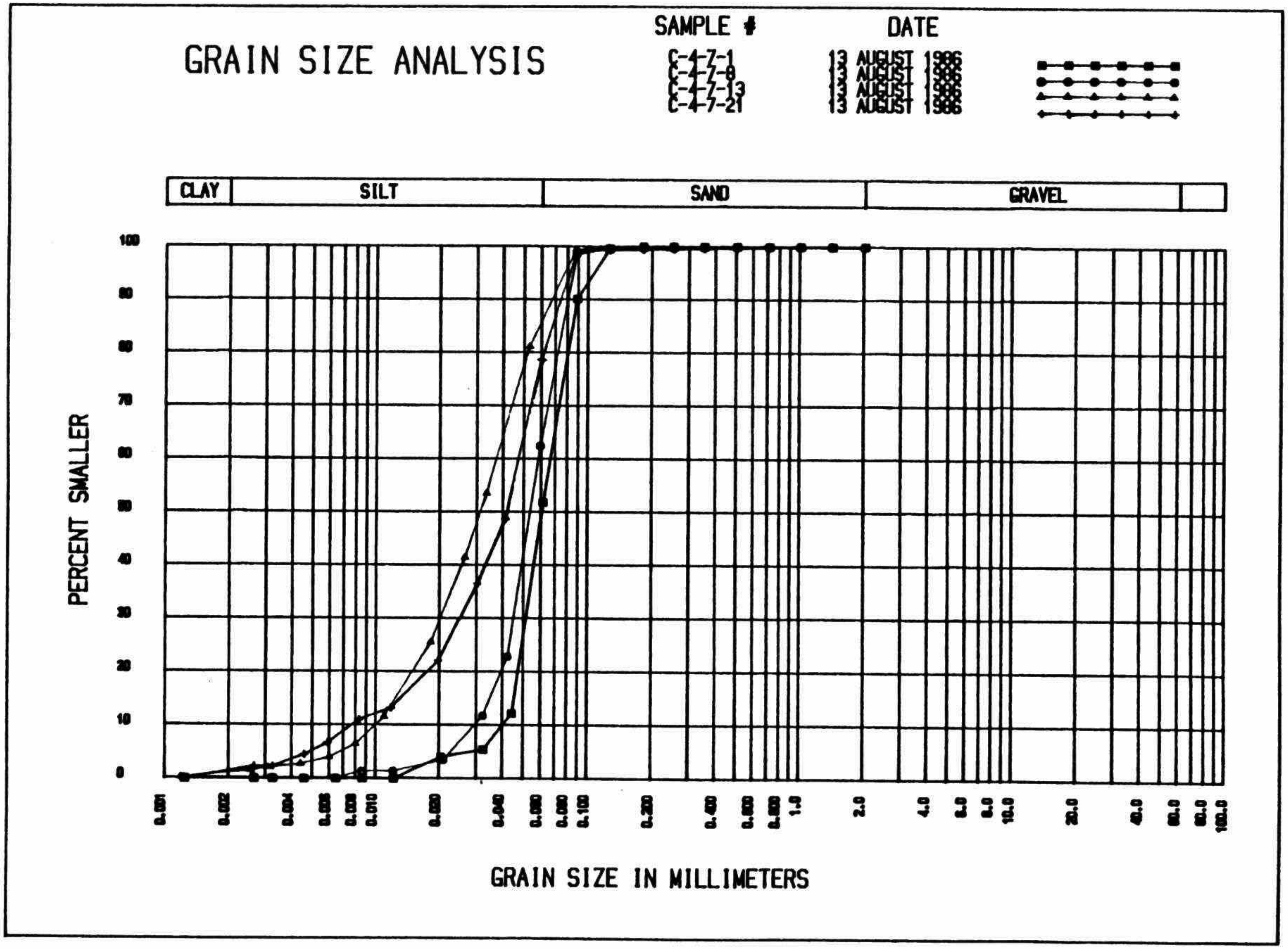
GRAIN SIZE IN MILLIMETERS


GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-4-7-1 13 AUGUST 1986 ■
C-4-7-8 13 AUGUST 1986 ●
C-4-7-13 13 AUGUST 1986 ▲
C-4-7-21 13 AUGUST 1986 ✦
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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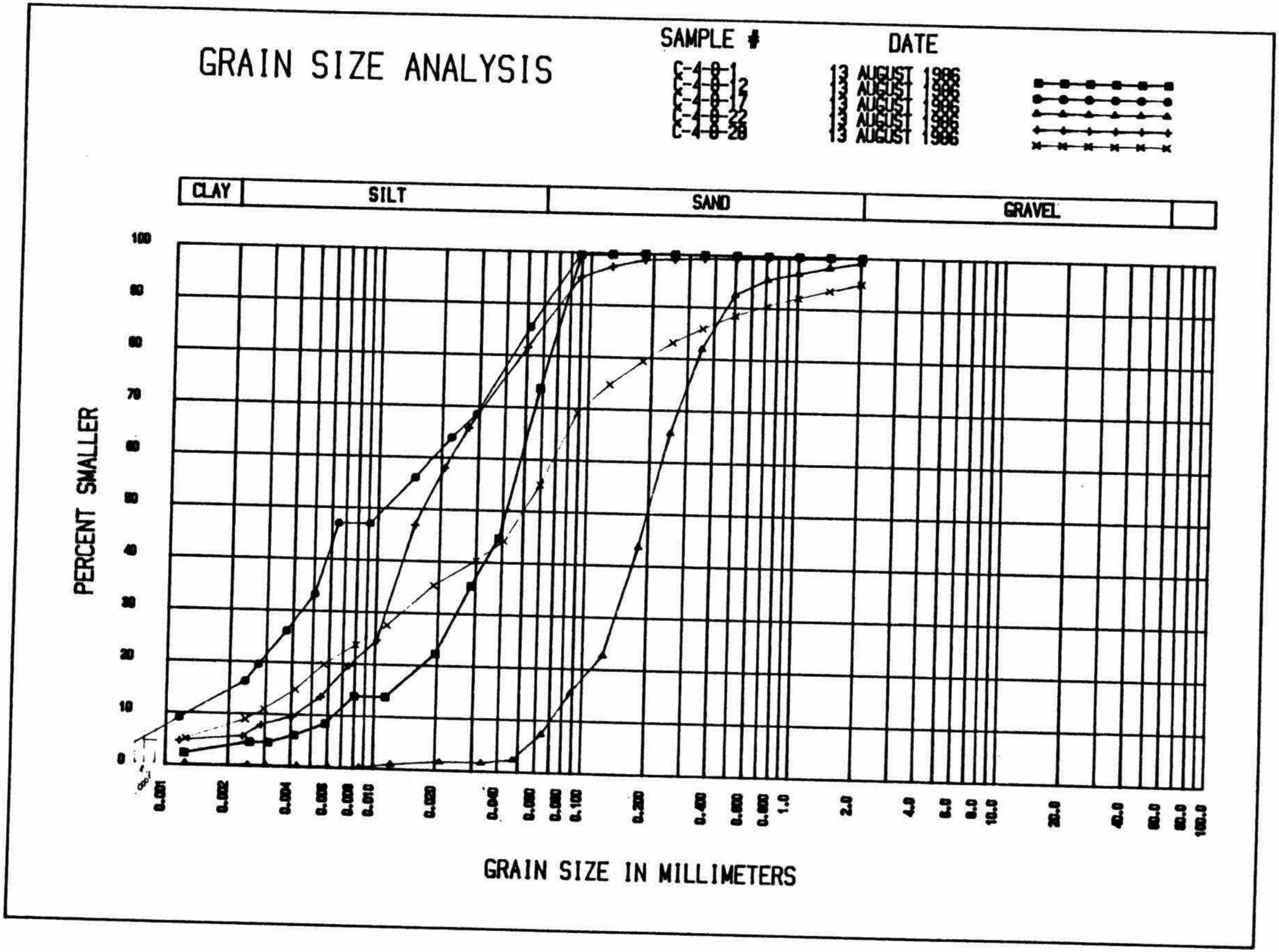
GRAIN SIZE IN MILLIMETERS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SAMPLE #
DATE
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C-4-8-12
C-4-8-17
C-4-8-22
C-4-8-28
13 AUGUST 1986
13 AUGUST 1986
13 AUGUST 1986
13 AUGUST 1986
13 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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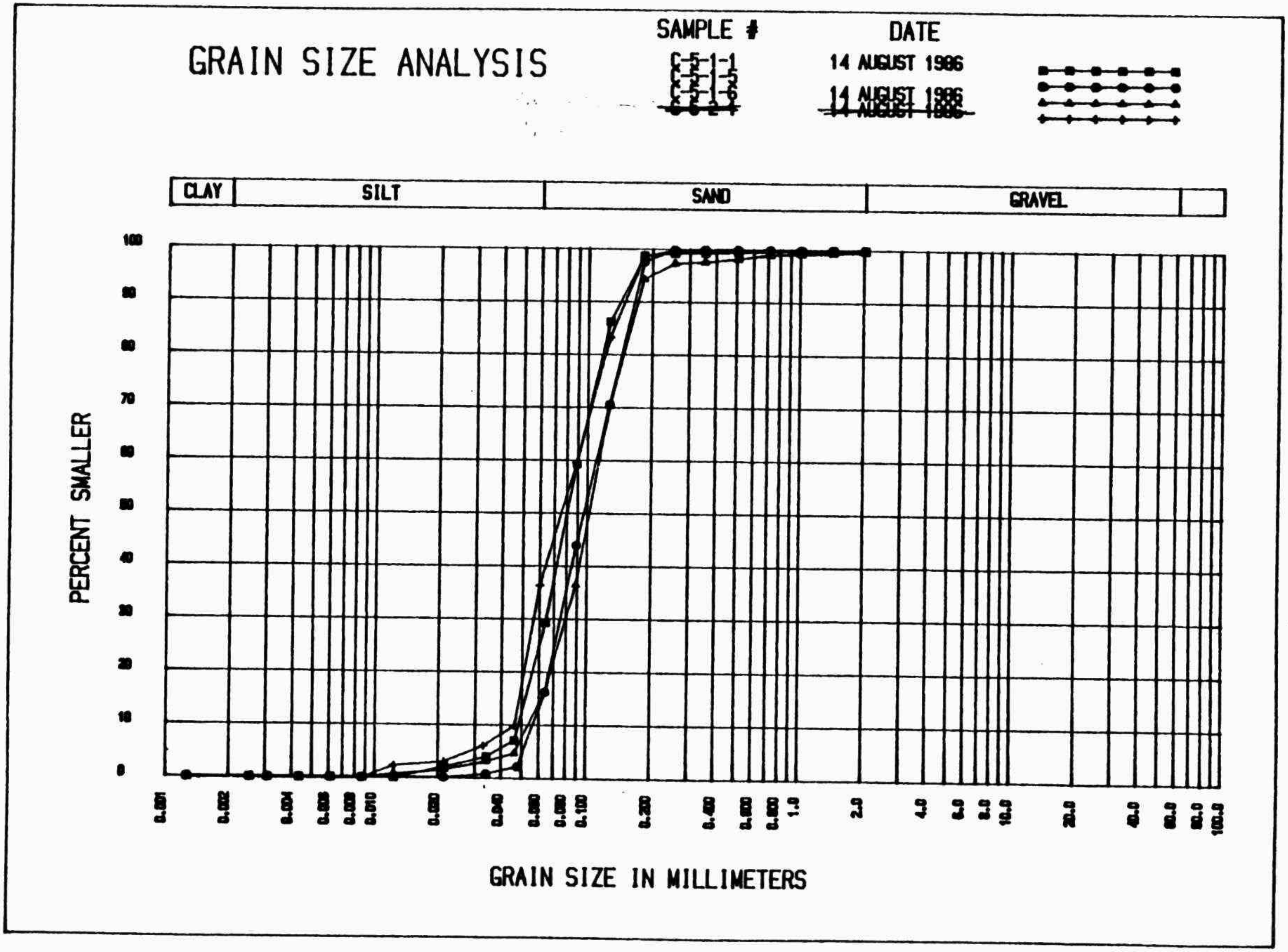
GRAIN SIZE IN MILLIMETERS


GRAIN SIZE ANALYSIS
SAMPLE #
DATE
C-5-1-1
C-5-1-5
C-5-1-6
14 AUGUST 1986
14 AUGUST 1986
14 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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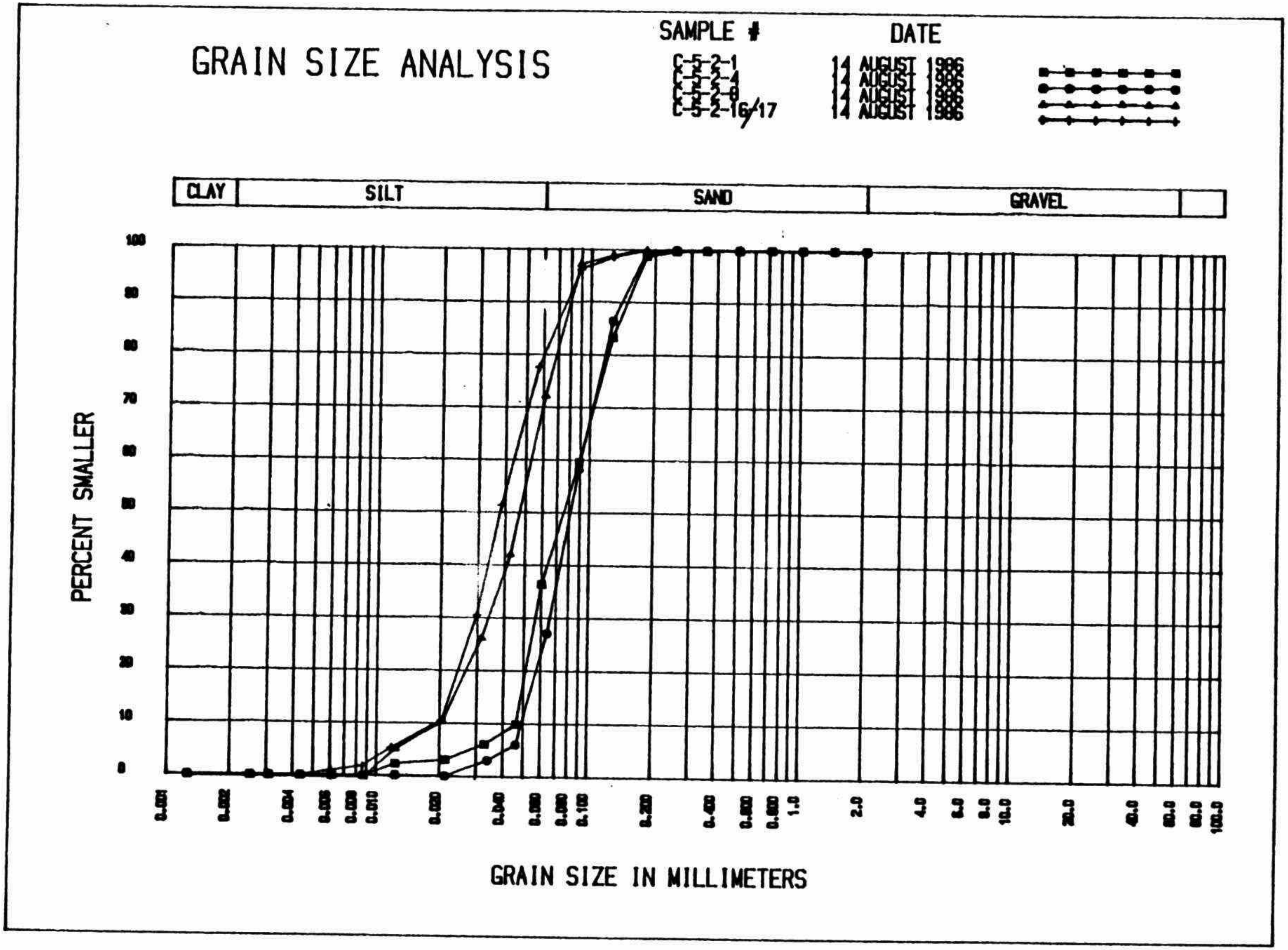
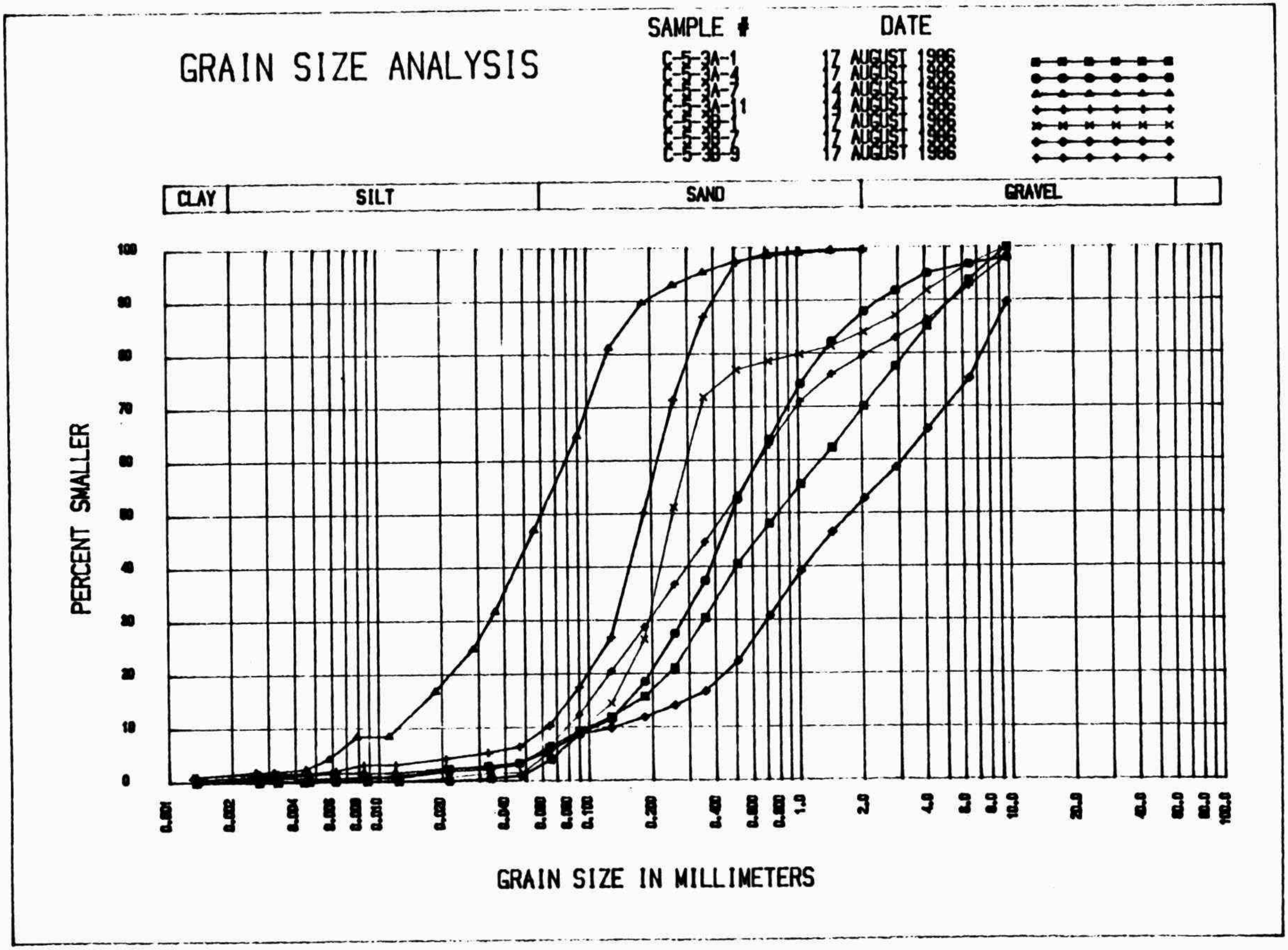
GRAIN SIZE IN MILLIMETERS

## GRAIN SIZE ANALYSIS

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DATE
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C-5-3A-4 17 AUGUST 1986 ●
C-5-3A-7 14 AUGUST 1986 ▲
C-5-3A-11 14 AUGUST 1986 +
C-5-3B-1 17 AUGUST 1986 ×
C-5-3B-7 17 AUGUST 1986 ◆
C-5-3B-9 17 AUGUST 1986 ◆
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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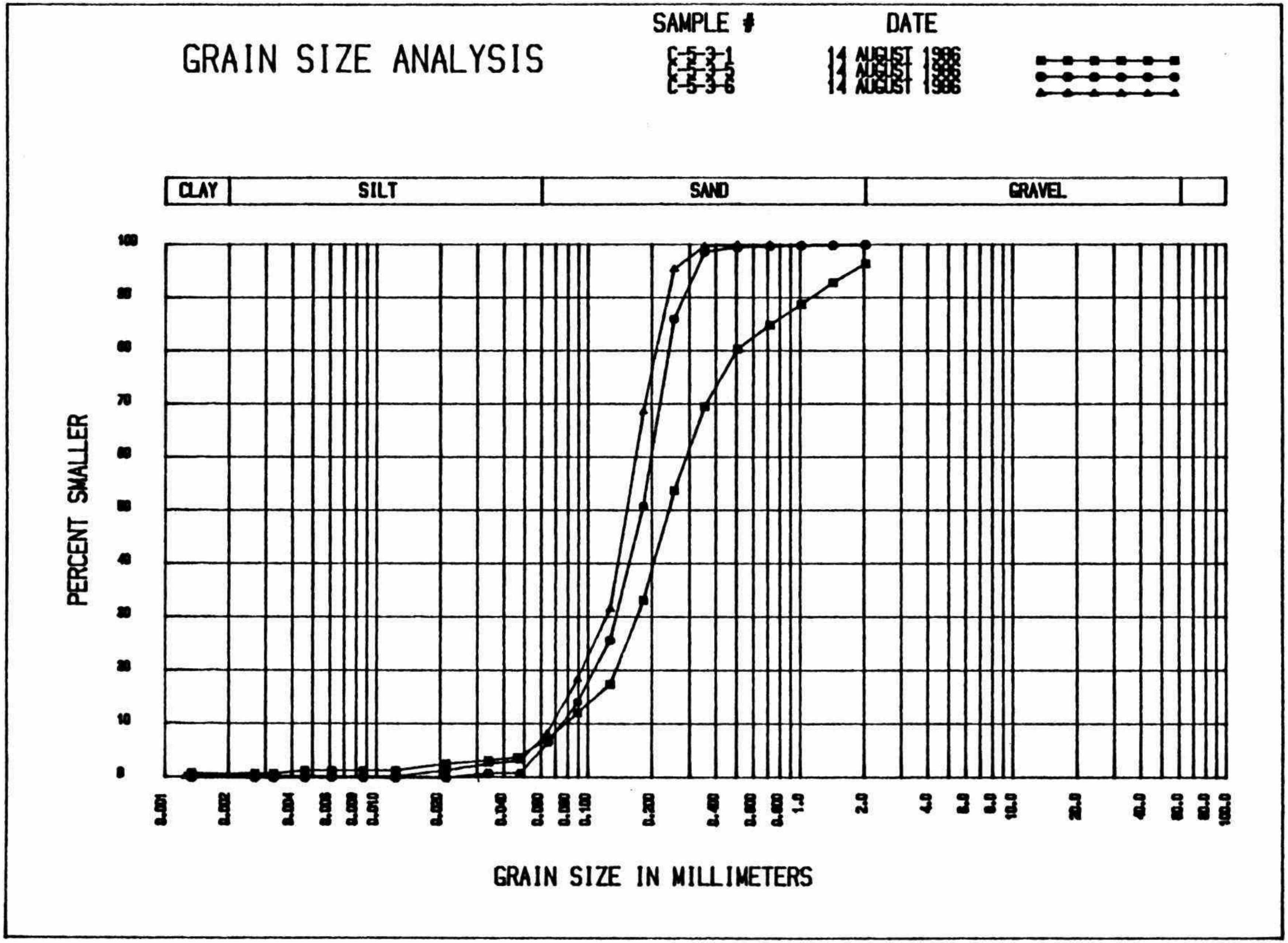
GRAIN SIZE IN MILLIMETERS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SAMPLE #
DATE
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C-5-3-5
C-5-3-6
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14 AUGUST 1986
14 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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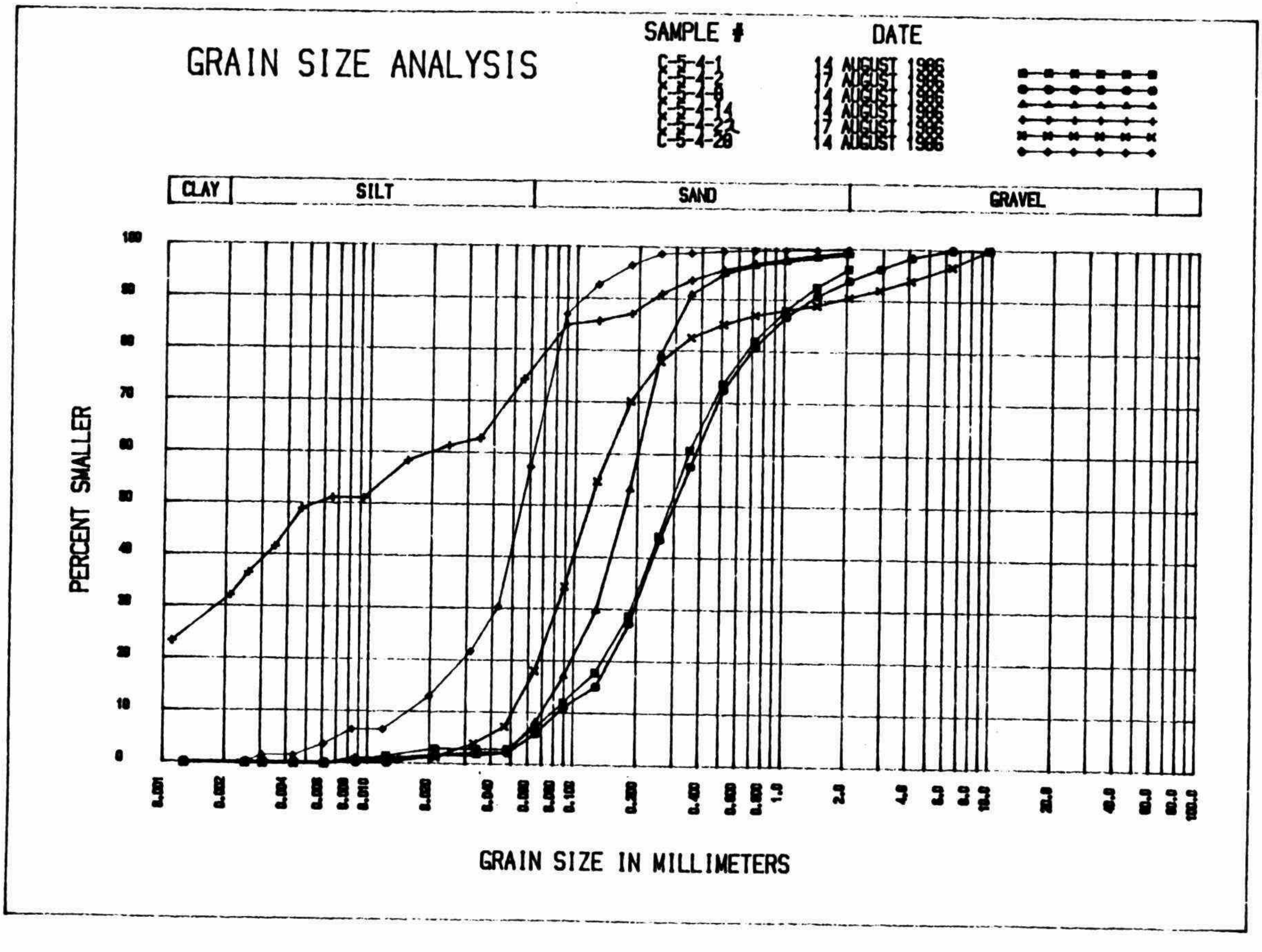
100.0
GRAIN SIZE IN MILLIMETERS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SAMPLE #
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C-5-4-6 14 AUGUST 1986 ▲
C-5-4-14 14 AUGUST 1986 +
C-5-4-22 17 AUGUST 1986 ×
C-5-4-28 14 AUGUST 1986 ◆
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
100
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80
70
60
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20
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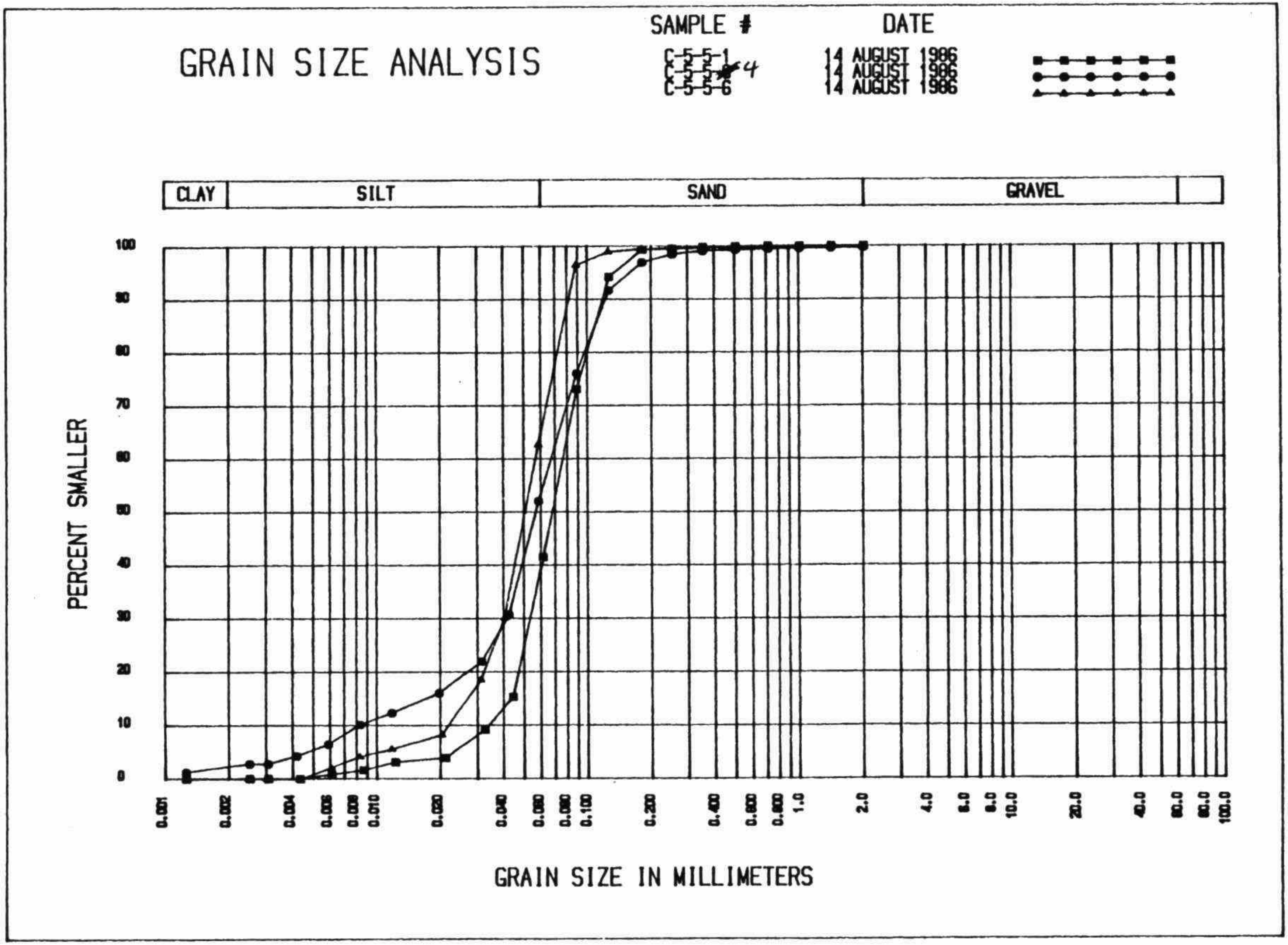
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C-5-5-4
14 AUGUST 1986
C-5-5-6
14 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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90
80
70
60
50
40
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20
10
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0.004
0.006
0.008
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0.400
0.600
0.800
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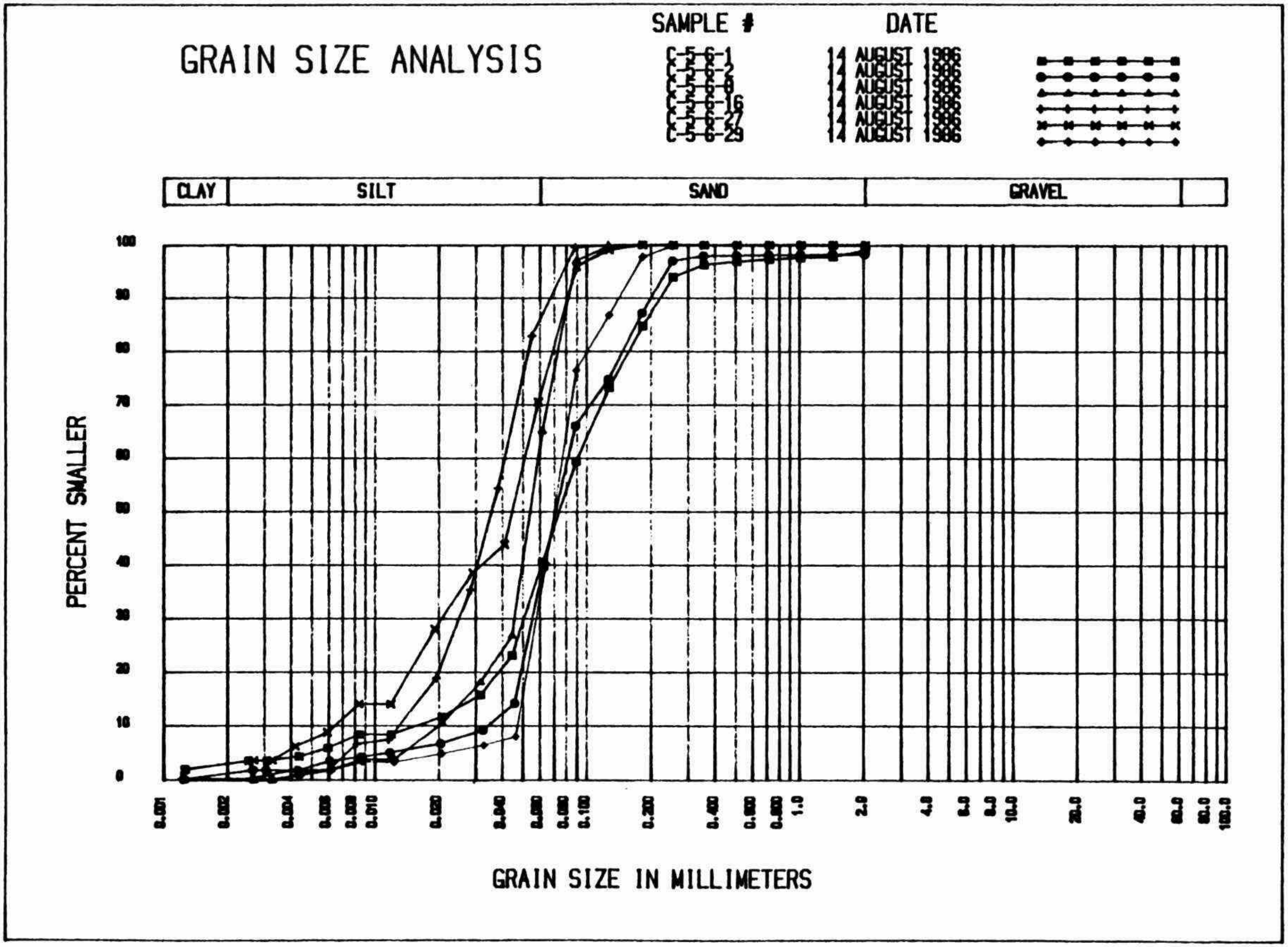
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C-5-6-27 14 AUGUST 1986
C-5-6-29 14 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
100
90
80
70
60
50
40
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20
10
0
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0.002
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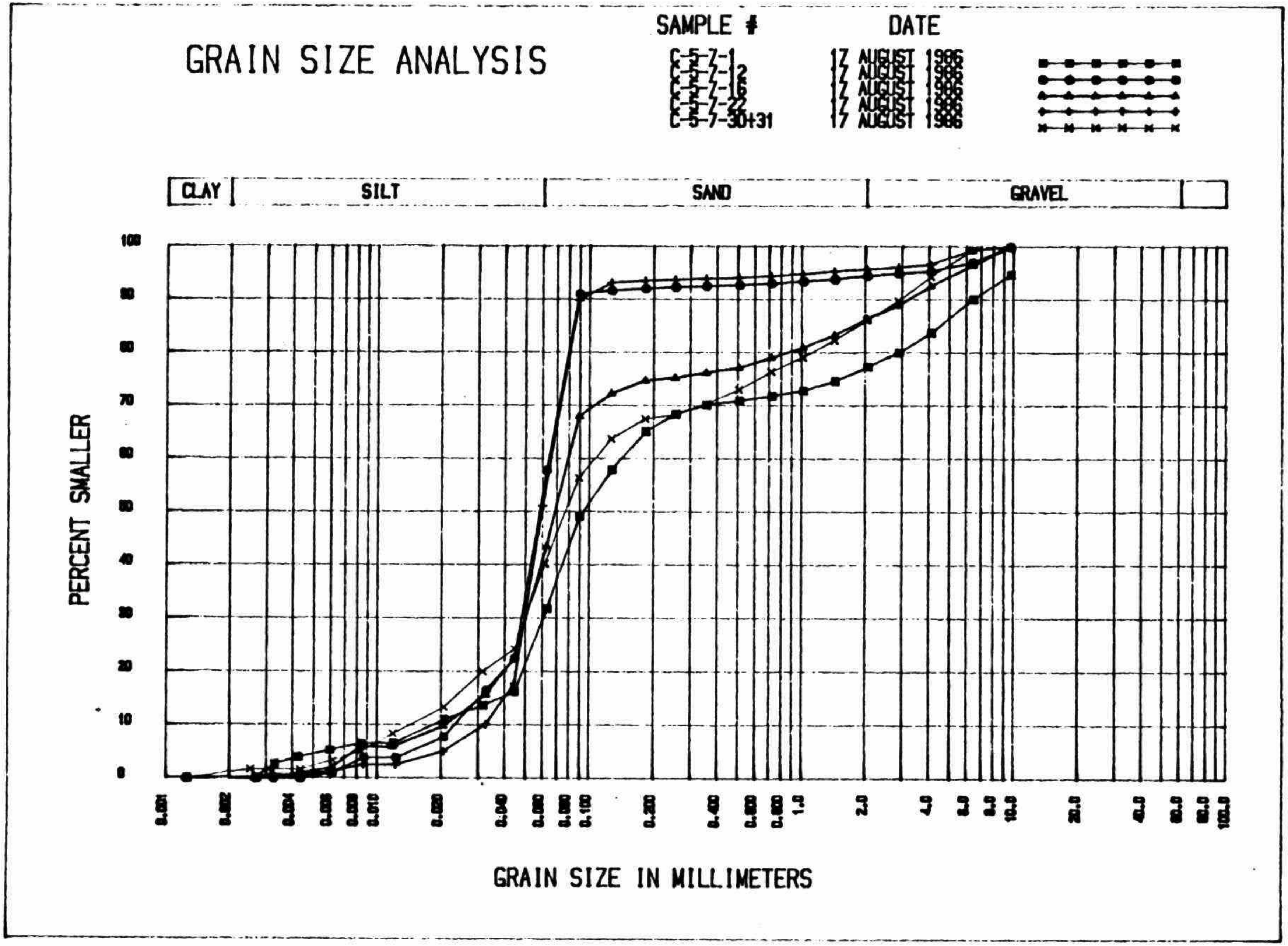
GRAIN SIZE IN MILLIMETERS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C-5-7-16
C-5-7-22
C-5-7-30+31
17 AUGUST 1986
17 AUGUST 1986
17 AUGUST 1986
17 AUGUST 1986
17 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
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90
80
70
60
50
40
30
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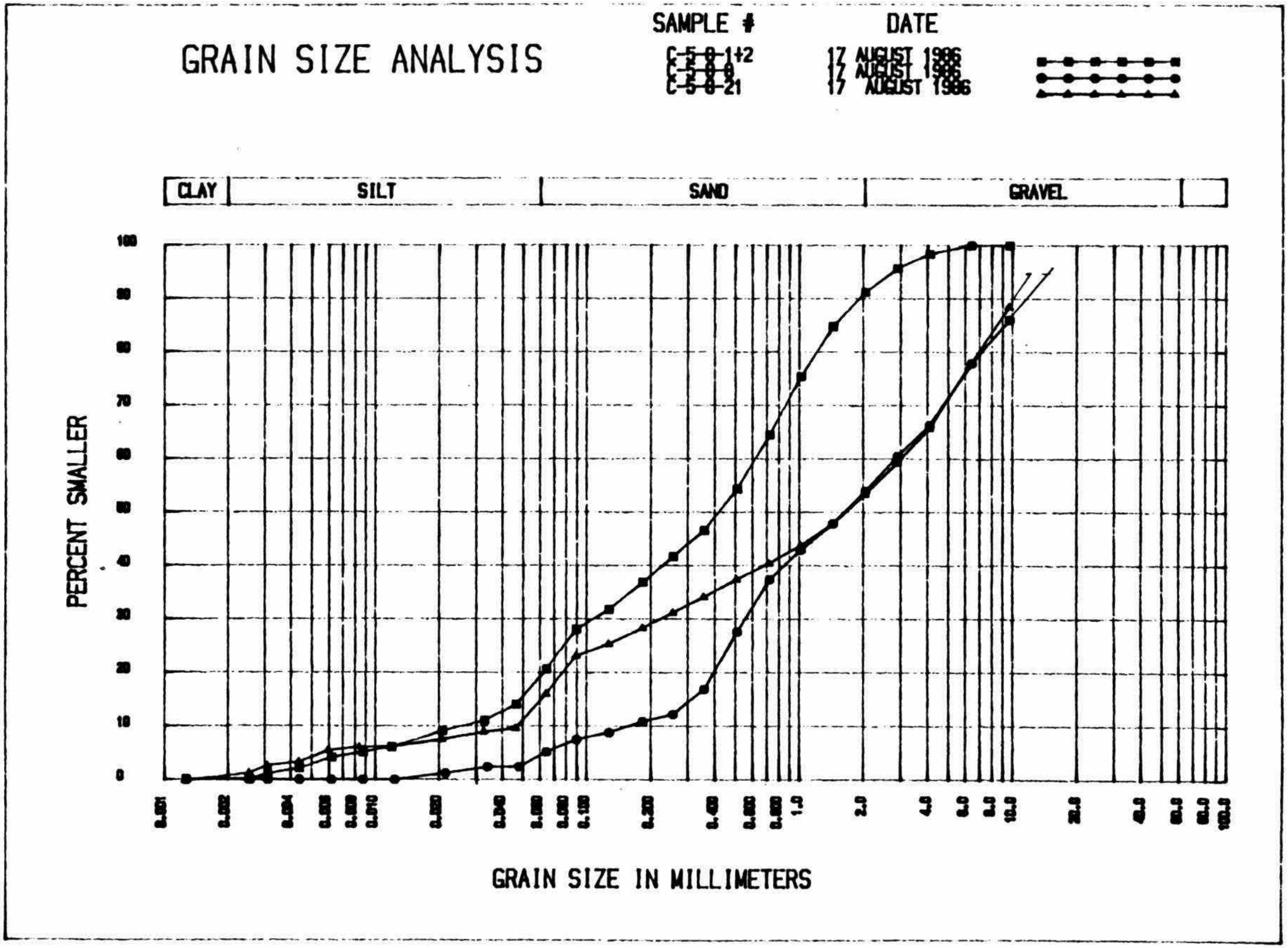
80.0
100.0
GRAIN SIZE IN MILLIMETERS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SAMPLE #
DATE
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C-5-8-8
C-5-8-21
17 AUGUST 1986
17 AUGUST 1986
17 AUGUST 1986
CLAY
SILT
SAND
GRAVEL
PERCENT SMALLER
100
90
80
70
60
50
40
30
20
10
0
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GRAIN SIZE IN MILLIMETERS

# Appendix C

# TECHNICAL NOTES

The packer slug tests required the development of special construction and field techniques. Because the field work was conducted during the winter and by one person, the field techniques described here greatly facilitated the task. These points are listed here along with some miscellaneous comments on equipment performance.

1. Because of the limited amount of clearance between the packer assembly and the inside of the well 5 cm (2 in) the packers were secured to the PVC pipe by cutting a groove at the top and bottom of each pipe and using a sailors rope whipping technique on the outside of the tubes.
2. Before the packers were inflated and when the riser pipes were being lowered or pulled out of the hole a 'C' clamp was used to prevent the assembly from falling down the hole.
3. The tubing performed flawlessly down to temperatures of -20°C..
4. A nylon measuring tape attached just above the top packer and secured at each pipe joint with nylon tape permitted depths to be monitored as the assembly was moved up the well. Tape corrections were required to compensate for the length of the upper packer, the space above the top of the testing interval, and the top of the casing above the ground so that subsurface depths could be easily kept track up. A "spread sheet" was set up noting "tape depths" and the corresponding subsurface test depths.

5. In order to simply and routinely displace water in the riser pipe since the packers were set an aluminum rod 1.9 cm (0.75") in diameter and 2.84 m (9.3 ft) in length was constructed in two sections which screw together. The rod was attached to a rope which passed through a pulley on the tripod. The slug was positioned at its initial position just at the static water level. Input signals from the transducer were monitored via a voltmeter to insure that the slug did not prematurely enter into the water.

6. Rope stoppers were positioned on the rope at intervals equal to the slug lengths upon entry and recovery the slug would travel only the required distance This permitted the slug to be routinely during the tests. The rope stoppers were checked periodically to ensure that they did not slip to allow additional aluminum rod to enter the water and yield greater than 1 meter displacement.

7. The tripod was made of 2" PVC pipe with end plugs and pins. A pulley was attached to the apex of the tripod. The feet of the tripod were positioned on aluminum plates which had a hole drilled in the center and the corners bent at 90$^{\circ}$. These plates were left on location for the duration of the test. In snow they were iced in and in the soil they were firmly implanted. This permitted easy and routine positioning of the tripod and slug assembly and negated the need to realign the equipment when the tests could not be completed in one day.

8. To protect the electronics from the cold and to ensure that the chart recorder operated at the correct speeds a cooler with a light bulb was used. The "cooler" was placed on its side and all the electronics were located inside. The lid was detached during tests but re-positioned when equipment had to be set up or adjusted. The electronics were kept indoors at night and were the first piece of equipment set up so that they would be warm.

9. The generator was placed on a tobaggon and lowered into a snow pit so that the noise of the engine could be muffled. A extension cord permitted the generator to be located as far as possible from the test site. The generator was properly grounded with a long copper rod hammered into the ground. Keeping the rod in line with the exhaust kept the rod warm and facilitated its removal from the frozen ground.

10. Equipment was hauled in on a double tobaggon (skid) which was constructed from two heavy duty 1.8 m (6 ft) long tobaggons positioned side by side. Sides with rope tie downs were put on around the skid to keep snow from packing in on the equipment and gear. The skid was hauled in on harnesses and with snow shoes until the dense spring snow pack permitted the use of a 3 wheel all terrain cycle. Snow mobiles were unavailable.

11. A shack was used to shelter both the operator and the equipment. It was constructed from press board with a 5 cm x 5 cm (2" x 2") frame bolted together. A roof and floor were also provided.

12. To prevent the transducer from decending into the hole beyond the depth at which it was positioned it was secured to the tripod. The packer inflation line was similarly secured so that it was taut and did not impede the slugs travel.

13. The tape was also secured to the tripod. The tape was reeled in as tests were performed.

14. Orange flagging (surveyors tape) was tied to the air inflation line so that it could be easily seen in the snow.

15. A "male" swagelock coupling was always put on the inflation line in the "female" end to prevent the treads in the line from being clogged with either dirt, ice, or snow.

16. The transducer was kept submerged as often as possible so that ice build up was minimal. It was also dried as best as possible at the end of each day.

17. All non-fragile equipment was buried in the snow at the end of each day. This prevented any possible vandalism from occurring.

A-2

# Aspects of the Contaminant Hydrogeology
# of the
# Woolwich Landfill Site

by

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Feb.6,1986

# ABSTRACT

The University of Waterloo is involved in a variety of studies at several Ontario landfill sites. One of these sites is the Woolwich Landfill Site located to the northeast of the City of Waterloo. Groundwater samples are analyzed for volatile aromatic hydrocarbons, chloride and total organic carbon (TOC) content. Volatile organic contaminant data are subject to variability which can make the interpretation of the data difficult. This variability is due in part to natural fluctuations in the contaminant levels and in part to sampling error. Five possible sources of error due to sampling and analysis techniques were examined in an earlier report by Travis and Barker, (1985). The purpose of this report was to follow up one of Travis's recommendations. Travis found that the standing water in a piezometer was enriched in volatile organic contaminants. Concentration levels dropped significantly after three well volumes were removed. In July 1985 Travis's experiment was repeated. The results of this experiment showed low organic contaminant concentration levels, less than 1.8 ppb. The concentration levels fluctuated, but they were too low to distinguish between natural short-term variability and sampling error. The remainder of the multilevel piezometer point were also sampled to determine if there were zones of higher contaminant concentrations that could be leaching through the piezometer tubing and increasing the apparent contamination of the standing water. No such zones were found, therefore this report is unable to confirm such an occurrence. However, based on the chloride data, which did decrease significantly as several well volumes were

removed, it is recommended that at least three well volumes be removed prior to sampling to obtain a representative sample of the aquifer.

During the sampling season of 1985 a new technique of sampling was tried. A double packer pump was assembled and installed in a fully screened Timco-type well. The purpose of the experiment was to determine if it was possible to effectively isolate a one meter interval of the well using the packers and to collect a groundwater sample representative of that short interval. The samples were compared with samples collected from a multilevel piezometer located one meter away. The results of the analysis showed a zone of high contaminant concentration present in the multilevel piezometer. The zone was lacking in the double packer samples. It was concluded that the packers could not isolate the interval and that the samples collected from the Timco well were representative of the average contaminant concentration over the length of the well.

In addition to this study, piezometers lying on the boundary of the landfill were sampled to get an indication of the type and concentration of contaminant input into the aquifer. The input was found to be highly irregular and complex. Chloride, TOC content and various aromatic hydrocarbons were present in high concentrations. There appears to be a good correlation between the concentrations of the aromatic hydrocarbons. Chloride content did not correlate well with the hydrocarbons, but correlated quite well with the TOC content. Chlorinated hydrocarbons were absent or at very low concentrations. The input reaches a maximum in the south east corner of the landfill.

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# Chapter I

# INTRODUCTION

The University of Waterloo is involved in the growing field of Hydrogeology. During the sampling season of 1985 four aspects of contaminant hydrogeology were investigated at one of the field locations, the Woolwich Landfill Site. The first aspect of the investigation was the monthly sampling of a dozen piezometers lying to the southeast of the landfill in order to define and monitor the leachate plume. The findings of that study are presented in a report entitled, "Monitoring the Woolwich Landfill Contaminant Plume", (Ross,1986).

The second aspect of the investigation was to follow up one section of an earlier report, (Travis,1985). This report dealt with possible sources of temporal variability that is found in groundwater samples. Travis found elevated contaminant concentrations in water that had been standing in the piezometer. The concentrations dropped significantly after several well volumes were removed. Travis suggested that contaminants may have been moving through the piezometer tubing from areas of high concentration to those of lower concentration. One piezometer was selected in July 1985 and sampled repeatedly over the course of the day to monitor fluctuations in the contaminant concentrations.

The third aspect of the summer's work was the testing of a new sampling technique which involved the use of a double packer sampling system installed in a fully screened well. The purpose of the experiment was to see if it was possible to isolate a section of the well and collect a groundwater sample representative of only that short interval. The fourth aspect of the Woolwich Landfill investigation was the collection of groundwater samples from piezometers lying along the edge of the landfill to obtain a picture of the type and distribution of the leachate at the source of input. This report contains the second,third and fourth aspects of the investigation. It is presented as two separate reports. The double packer sampling experiment and the leachate input data are written as one report. The temporal variability study is written up separately. The reports have been written to stand independant of each other, therefore each begins with a more detailed introduction and a set of conclusions. A summary of the conclusions and recommendations is placed at the end of the second report.

# Short Term Variability at Piezometer ML-16

## Chapter II

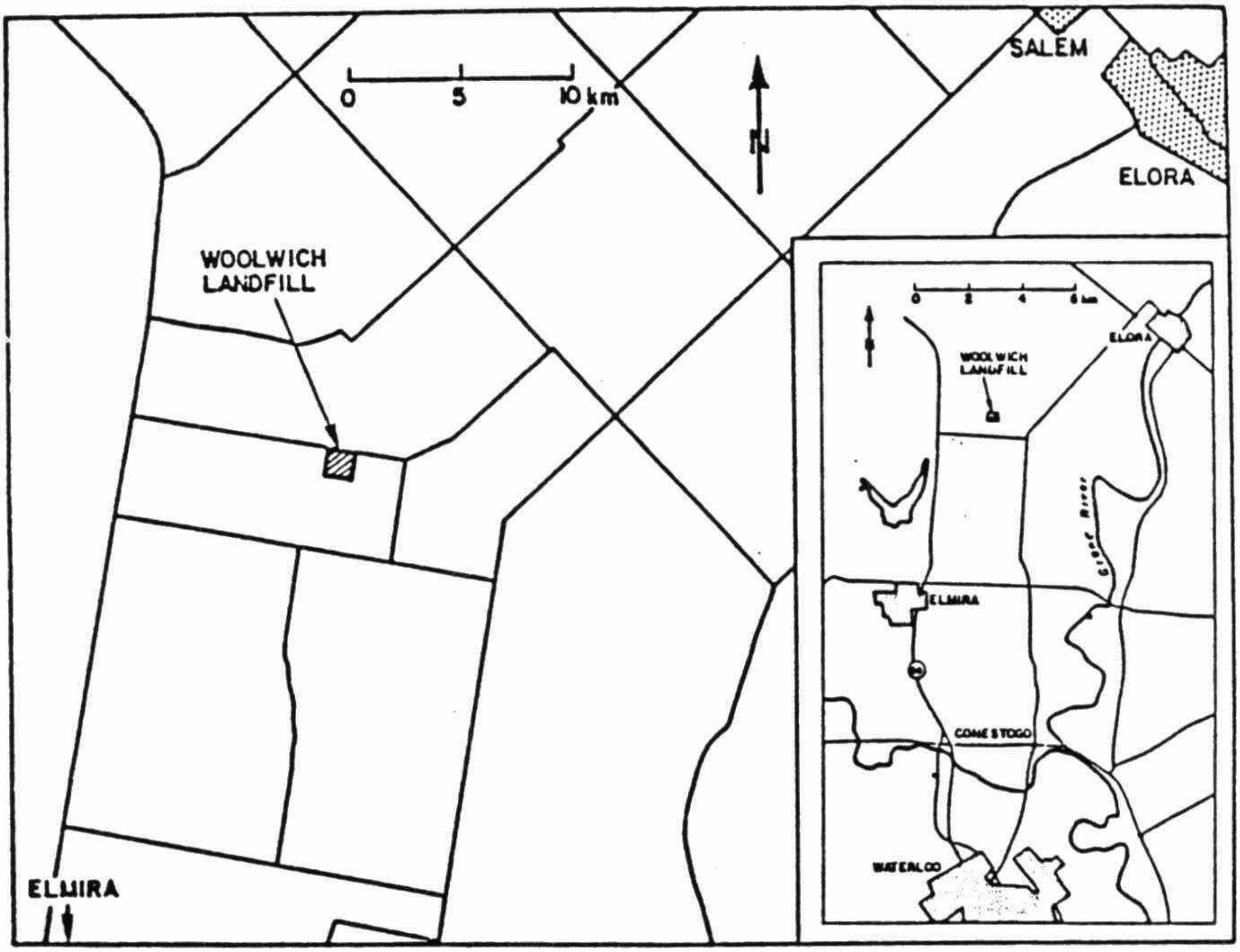
## INTRODUCTION

Volatile organic contaminant data for groundwater samples is subject to variability due in part to natural variability and in part to sampling, storage and analysis techniques. Since it is the natural variability we are interested in, it is important that we can distinguish between the two sources and can then minimize sampling error.

A report entitled, " An Examination into Possible Sources of Volatile Organic Contaminate Variability" (Travis & Barker, 1985) researches five possible sources for the variability in the data. This report is a follow up to one aspect of that investigation and will not repeat in detail what is found in the Travis report. For a more detailed account of the locations and sampling methods used, the reader is referred to that report. The sampling site was the Woolwich Landfill, located in Woolwich Township, Ontario (Figure 1).

Travis suggested some variability may be caused by the collection of an unrepresentative sample of groundwater, due to inadequate flushing of the standing water in the piezometer. On August 29,1984 samples were taken from tube #4 of multilevel piezometer ML-16 (Figure 2). The tube was sampled fourteen times at half hour intervals over the course of a day. Travis's data indicated that there was intially higher concentrations of contaminants that decreased significantly as three or four volumes were removed. The samples were analyzed for chloroform, 1,1,1-trichloroethane, carbon tetrachloride, trichloroethylene and chloride (Figure 3). Travis suggested that the

Figure 1: **Location of Woolwich Landfill Site.**



higher concentrations found in the standing water may be due to diffusion of the contaminants through the polyethylene piezometer tubing from highly contaminated water above the intake interval. No such highly contaminated water was found at the time. Travis recommended that the experiment be repeated.

The purpose of this report was to determine whether the variablility found in data for groundwater samples collected over a short time span was due to natural variance or simply a reflection of the effects of flushing a piezometer and to investigate the possibility of contaminants leaching into the standing water from contaminated water above the intake interval. One tube was selected and sampled repeatedly to observe changes in concentrations over the course of one day. In addition, the other eight levels of the piezometer were flushed well and sampled to search for a zone of high contaminant concentrations. On July 22,1985, tube #4 of multilevel piezometer ML-16 was sampled eleven times during a 5 hour 40 minute interval.

Figure 2: **Piezometer Locations at the Woolwich Landfill Site.**

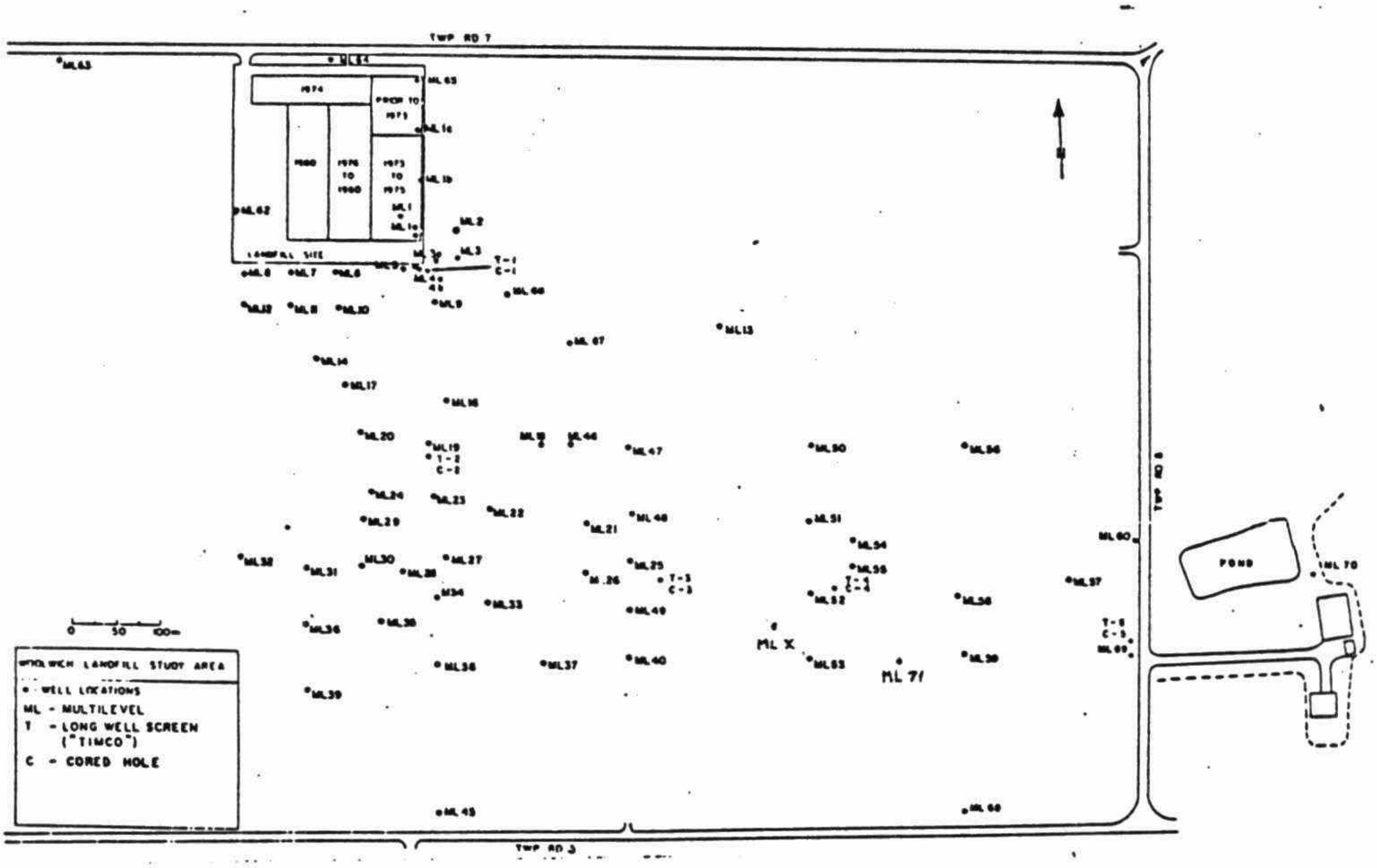
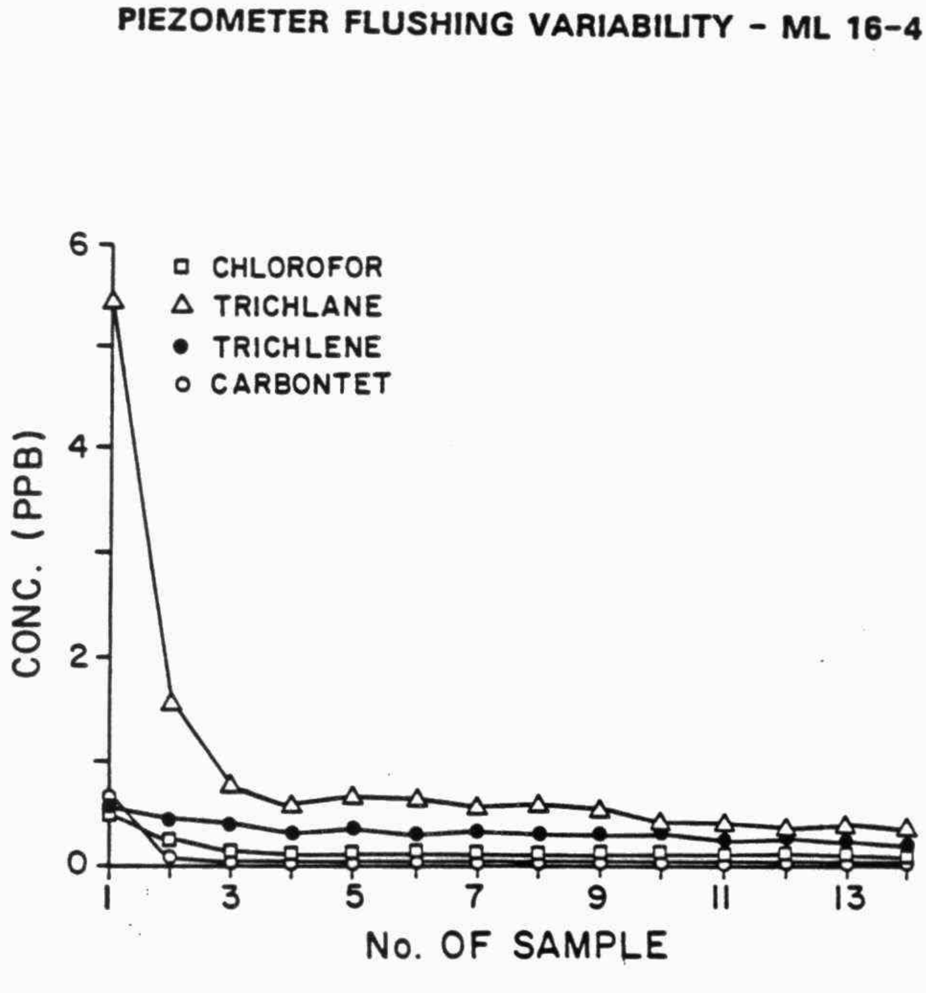


**Figure 3:** Short Term Variability At ML-16-4 August 29, 1984.



# Chapter III

## METHOD

ML-16 is a multilevel bundle piezometer consisting of nine separate tubes extending down to different depths. All nine levels were sampled using a gas-drive sampling device.(See Travis ch.4 for a complete discussion of sampling equipment). All sample bottles, 60 ml hypovials and 20 ml bottles, were kept cool (4 C) prior to and after sampling. The triple tube was inserted to within several inches of the bottom of the tube and the packer was inflated to 100 psi. Pumping was done at 40 psi to minimize volatization. Duplicates were taken when possible. The tubes were flushed three times before sampling with the exception of #4. For tube #4 a sample was taken from each well volume extracted. The first three samples were taken from tube #4 at 20 min intervals, then samples were taken at roughly 45 min intervals. The other eight tubes were only sampled once. The hypovials were sealed immediately with a teflon faced silicon septa and cap which was crimped on. Care was taken to avoid any headspace in the hypovials. The samples were analyzed in the lab for carbon tetrachloride, chloroform, 1,1,1-trichloroethane, trichloroethylene and tetrachloroethylene, using a pentane-extraction step, followed by gas chromatography. This is the same technique used to analyze Travis's samples. The samples were also analyzed for aqueous total organic carbon (TOC) on a Dohrmann Carbon Analyzer model DC-80 and for chloride on a Colorometric Analyzer.

## Chapter IV

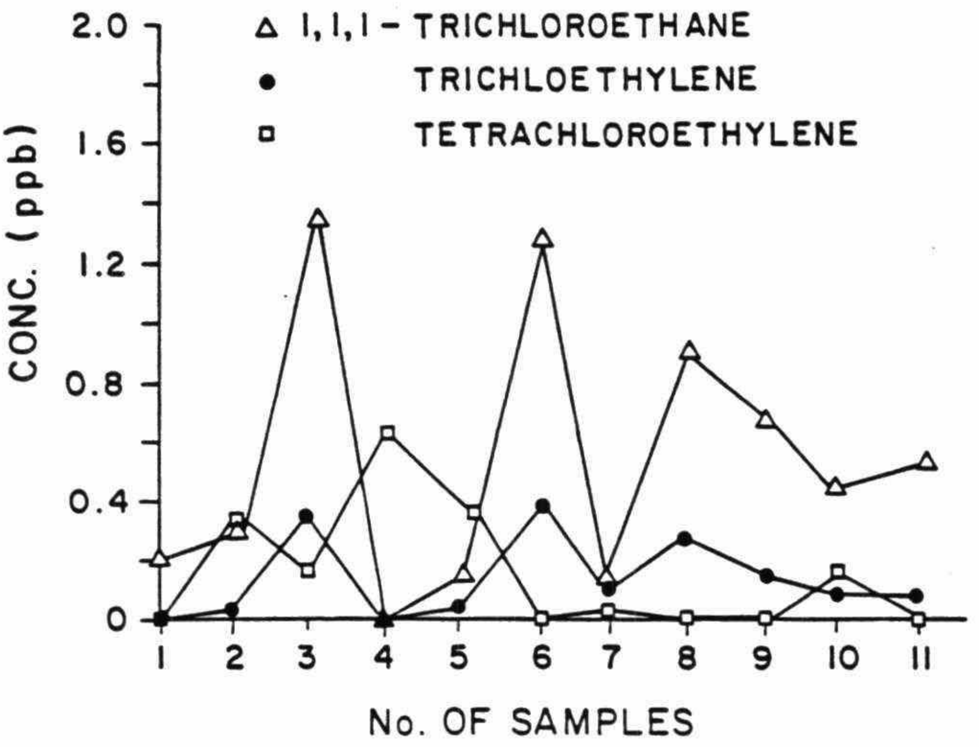
## SUMMARY

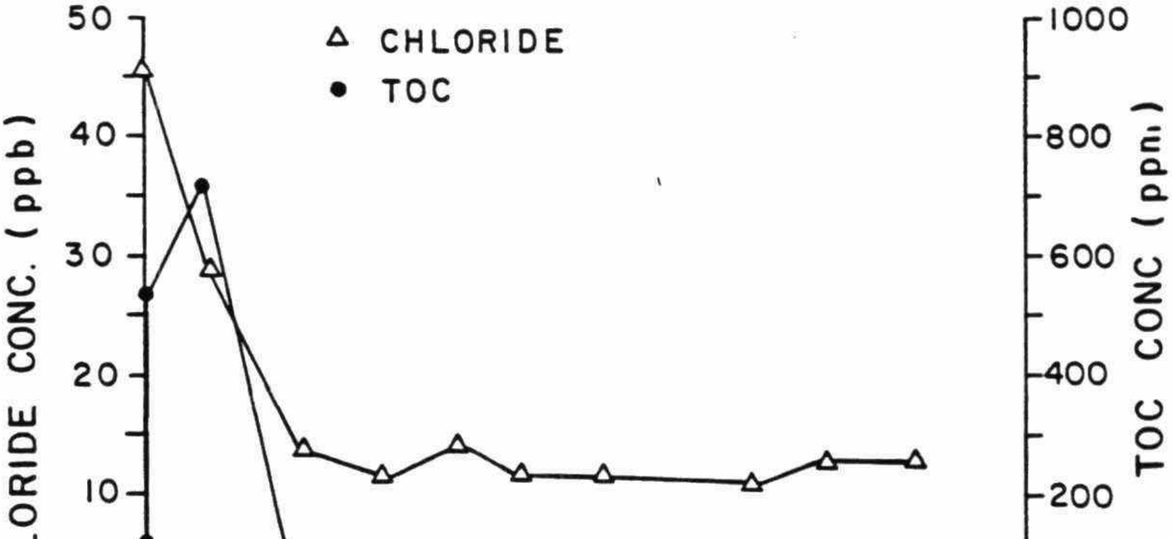
The data obtained for the volatile organics did not correlate well with previous findings. In ML-16 #4 carbon tetrachloride was absent. Chloroform was present but below detection limits. 1,1,1-trichloroethane ranged from 0.0-1.6 ppb, with a random fluctuation over time. Trichloroethylene ranged from below detection levels to 0.4 ppb and tetrachloroethylene ranged from below dectection levels to 0.6 ppb, both with random fluctuation over time. (Table 1). There was no evidence of the standing water becoming enriched in volatile organic contaminants, as suggested by Travis (Figure 4).

Similar results were found for the other eight tubes. Chloroform was below detection levels, carbon tetrachloride was absent. 1,1,1-trichloroethane ranged from 0.0-1.7 ppb, trichloroethylene ranged from 0.0-0.6 ppb and tetrachloroethylene ranged from 0.0-025 ppb (Table 2). No zones of higher contaminant levels were observed above or below tube #4.

When the data for ML-16-4 is plotted as concentration vs time, the concentrations of 111,trichloroethane and trichloroethylene follow the same trends in fluctuation over time (Figure 4). Tetrachloroethylene fluctuates independantly from the other contaminants. The variation in duplicate samples is almost as great as the overall sample variance. At such low contaminant levels it is difficult to separate the sampling and analytical error from the short term temporal variability.

Figure 4: Variability at ML-16-4 July 22, 1985.





The data for the TOC and chloride analysis does show the trend towards higher initial concentrations that Travis observed. The initial well volume removed from tube #4 had 528.1 ppm TOC and 45.5 ppm of chloride. The second volume had 726.4 ppm TOC and 29.4 ppm of chloride. The third volume had 6.9 ppm TOC and 13.9 ppm of chloride. After the third sampling the chloride values fluctuated between 13.9 -12.6 ppm. The TOC values were slightly more erratic, but seem to stablize in the 4.3-6.0 ppm range with one anomalous value of 17.2 ppm from the fifth sample collected (Figure 5).

The TOC values for the tubes at other levels are all higher than tube #4. Tube #3 is the highest at 72.6 ppm TOC. Tubes #5-#9 vary from 11.3-31.6 ppm. Tube #2 is the exception with 5.5 ppm TOC. The chloride at other levels tended to be slightly lower than tube #4, varying from 7.2-12.0 ppm. Again tube #2 is the exception, it is higher than surrounding tubes with 16 ppm chloride (Table 3).

## Chapter V

## CONCLUSIONS AND RECOMMENDATIONS

Since neither higher initial concentrations of volatile organic compounds in the standing water, nor any zones of higher contaminant concentrations were found, no definite conclusions can be drawn on the possibility of volatile organics leaching from one zone into another through the piezometer tubing. Data obtained from the TOC and chloride analysis tend to support the idea that standing water becomes enriched in contaminants. Higher zones of TOC were found surrounding the point of interest, however the concentrations found in these zones was not nearly as high as the concentrations found in the standing water. It is possible that the water in the tube has been standing for some time and is representative of water that has flowed through the site previously. Sampling at other well sites in the area has shown that TOC values from the same tube can vary from 11.0-111.0 ppm in one month. The long term variability of contaminant concentration is large. The short term variability is also significant. Values tend to stay in a narrow range after adequate flushing, but tend to fluctuate slightly from one sampling to the next. However, concentrations for duplicate samples also fluctuate. This indicates that there is still some significant error in the sampling technique. A slight difference in the temperature a sample is subjected to may be enough to lose some of the volatile organics.

This report concludes that the standing water in a tube is not a representative sample of the water in the aquifer at the time of sampling. It seems advisable to remove at least three well volumes of water before collecting a sample. It is not possible to conclude at this point what is responsible for the higher concentrations of contaminants found in standing water. It may be of interest to collect standing water from all the tubes several times over the course of the summer to determine if higher concentrations of contaminants tend to get trapped in the tubes. Further sampling should be done to try to establish the effect a zone of contaminant enriched water has on the other zones in the vicinity of a piezometer. A piezometer with higher levels of contamination should be choosen so that the effects of short-term variability can be distinguished from the effects of sampling error.

## Table 1: Chlorinated Hydrocarbon Variability - ML-16-4

| Sample I.D. | Time min | CHCl3 ug/l | TCEA ug/l | CCL4 ug/l | TCEY ug/l | PER ug/l |
|---|---|---|---|---|---|---|
| ML-16-4-A | 0 | — | 0.20 | a | a | a |
| ML-16-4-B | 18 | — | 0.31 | a | 0.04 | 0.33 |
| ML-16-4-C1 | 38 | — | 1.36 | a | 0.37 | 0.18 |
| ML-16-4-C2 | 38 | — | 0.92 | — | 0.16 | a |
| ML-16-4-D | 70 | — | — | a | a | 0.64 |
| ML-16-4-E | 170 | — | 0.19 | a | 0.05 | 0.38 |
| ML-16-4-F1 | 190 | — | 1.26 | a | 0.42 | a |
| ML-16-4-F2 | 190 | — | 0.32 | a | 0.10 | a |
| ML-16-4-G1 | 225 | — | 0.17 | a | 0.12 | 0.05 |
| ML-16-4-G2 | 225 | — | — | a | a | 0.34 |
| ML-16-4-H2 | 258 | — | 0.91 | a | 0.27 | a |
| ML-16-4-H2 | 258 | — | 1.00 | a | 0.28 | a |
| ML-16-4-I1 | 285 | — | 0.66 | a | 0.19 | a |
| ML-16-4-I2 | 285 | — | 1.11 | a | 0.31 | a |
| ML-16-4-J1 | 320 | — | 0.43 | a | 0.12 | 0.19 |
| ML-16-4-J2 | 320 | — | 1.58 | a | 0.42 | 0.26 |
| ML-16-4-K | 340 | — | 0.57 | a | 0.11 | a |

CHCl3 - Chloroform
TCEA - 1,1,1-Trichloroethane
CCl4 - Carbon Tetrachloride
TCEY - Trichloroethylene
Per - Tetrachloroethylene
— - below detection levels
a - absent

Table 2: Chlorinated Hydrocarbon Concentrations - ML-16

| Sample I.D. | CHCl3 ug/l | TCEA ug/l | CCl4 ug/l | TCEY ug/l | Per |
|---|---|---|---|---|---|
| ML-16-1 | — | a | a | a | 0.25 |
| ML-16-2 | — | 1.15 | a | a | 0.08 |
| ML-16-3A | — | 1.71 | a | 0.22 | 0.13 |
| ML-16-3B | — | 1.41 | a | a | 0.13 |
| ML-16-4 | see Table 1 | | | | |
| ML-16-5A | — | 0.91 | a | 0.57 | a |
| ML-16-5B | — | 0.71 | a | a | a |
| ML-16-6 | no sample collected | | | | |
| ML-16-7 | — | — | a | a | a |
| ML-16-8A | — | — | a | a | 0.17 |
| ML-16-8B | — | 0.20 | a | 0.06 | a |
| ML-16-9A | — | 0.37 | a | a | a |
| ML-16-9B | — | 0.54 | a | 0.04 | 0.13 |

CHCl3 - Chloroform
TCEA - 1,1,1-Trichloroethane
CCl4 - Carbon Tetrachloride
TCEY - Trichloroethylene
Per - Tetrachloroethylene
— - at blank levels
a - absent

Table 3: Toc and Chloride data for ML-16.

| Sample I.D. | Chloride<br>ppm | TOC<br>ppm |
|---|---|---|
| ML-16-2 | 16.7 | 5.5 |
| ML-16-3 | 12.0 | 72.6 |
| ML-16-4A | 45.5 | 528.1 |
| ML-16-4B | 29.4 | 726.4 |
| ML-16-4C | 13.9 | 6.9 |
| ML-16-4D | 12.6 | 6.0 |
| ML-16-4E | 13.9 | 17.2 |
| ML-16-4F | 12.6 | 5.0 |
| ML-16-4G | 12.6 | 5.2 |
| ML-16-4H | broken | |
| ML-16-4I | 12.2 | 4.3 |
| ML-16-4J | 13.6 | 4.8 |
| ML-16-4K | 13.6 | 6.0 |
| ML-16-5 | 9.7 | 24.5 |
| ML-16-6 | 8.9 | 11.3 |
| ML-16-7 | 7.2 | 31.6 |
| ML-16-8 | 7.9 | 28.2 |
| ML-16-9 | 9.5 | 25.1 |

A-3

# Testing of the Double Packer Sampling System at the Woolwich Landfill Site

And

# Monitoring the Leachate Input From the Woolwich Landfill Site

# Chapter I

## INTRODUCTION

Landfills are responsible for a wide variety of contaminants found in ground water. The University of Waterloo is investigating the nature and extent of leachate plumes in aquifers at several waste disposal sites in Ontario. One of these sites is the Woolwich Landfill, located just north east of the City of Waterloo. Waste has been dumped in trenches 7-10 meters above the watertable and covered with sand at least once a week since the mid 1960's. The University has installed an extensive network of 71 multi-level piezometers around the landfill to provide a three dimensional picture if the distribution of contaminants (Figure 2). In addition to the multilevel piezometers, the University has also installed five Timco type wells, made of 5 cm in diameter polyvinyl chloride (PVC) pipe. These wells are screened over a distance of 25-45 feet. The purpose of these wells is to provide a bulk water sample from the aquifer. The wells are also large enough to be used to measure directly the lateral groundwater velocity. The multilevel piezometers provide a water sample from a very specific elevation. The water samples are analyzed in the lab for various aromatic and chlorinated hydrocarbons, chloride content and total aqueous organic carbon (TOC). The distribution of the contaminants in the aquifer is complex and irregular. High organic concentrations near the landfill give way to much lower concentrations within 100 meters, due primarily to dispersion through dilution and possibly biodegradation of some of the volatile aromatic hydrocarbons.

The temporal variability, both short-term and long-term, is significant. This variability has been attributed largely to variability in the input from the landfill. During the sampling season of 1985, the multilevel piezometers that lie along the edge of the landfill were sampled to get a picture of the distribution of contaminants as they come out of the landfill. In addition, a new method of sampling which would be more time and cost efficient was tried. One of the Timco wells, T-1, lies at the south east corner of the landfill, 2 meters away from two multilevel piezometers, ML-4a and 4b. A one meter interval was isolated in well T-1 using a double packer in situ pump. The interval was sampled over a number of days. Points in the multilevel piezometers, corresponding in depth to the T-1 interval were also sampled. The experiment was conducted at three depths. The purpose of the experiment was to see if it was possible to pack off a short interval in a open well and collect a water sample representative of the aquifer in only that interval. The benefits of this method of sampling would be reduced cost in well installation and simplification of sampling by eliminating the neccessity of having to move the sampling device from one tube to another to sample different depths.

# Chapter II

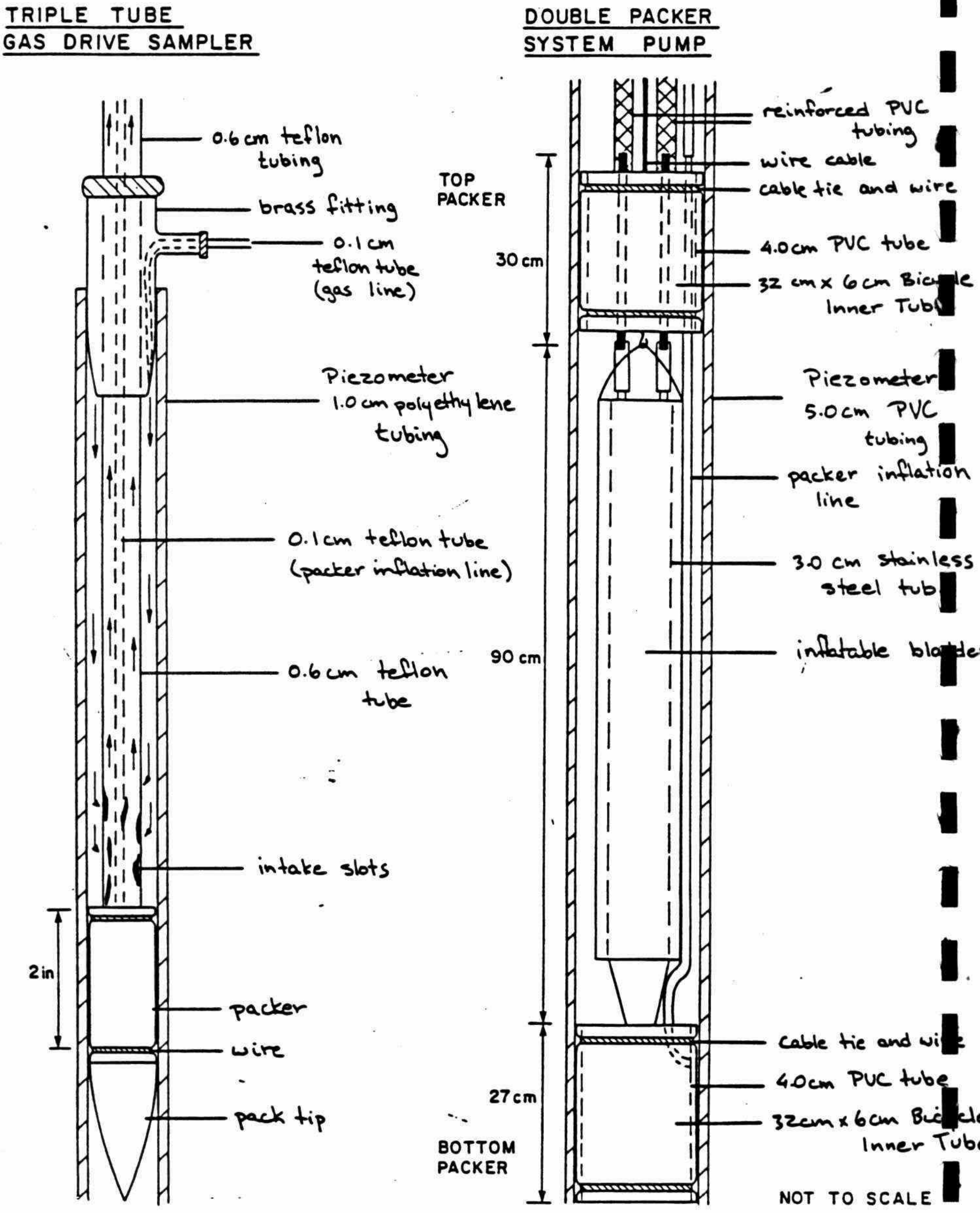
# METHODS AND EQUIPMENT

## 2.1 Sampling Multilevel Piezometers with the Triple Tube Gas Drive Sampling Device

The multilevel piezometers installed at the Woolwich land fill consist of 9-10 polyethylene tubes, 1 cm in diameter surrounding a central tube of 1.2 cm PVC plastic. The bottom 15-30 cm of the tubes are slotted and wrapped with a fine nylon screen. The depth to the water table around the landfill is 12-16 meters. It was neccessary to use a gas driven sampler to collect samples. The triple tube sampling device consists of a 0.1 cm diameter teflon spaghetti tubing inside a 0.6 cm diameter teflon tube. A 5 cm long packer with a brass or stainless steel tip is connected to the 0.1 cm tubing. The packer is lowered to within several inches of the bottom of the piezometer tube and inflated to 100 psi with nitrogen gas through the 0.1 cm tube. The top of the piezometer is sealed with a brass fitting through which gas is introduced into the the piezometer once the packer is inflated. The gas is forced between the polyethylene tube and the 0.6 cm teflon tube. The teflon tube is slotted at the bottom and the water in the piezometer is forced through these slots by the gas pressure and up the teflon tube to the surface where it is collected (Figure 5).

When the packer is deflated the piezometer recharges. Three well volumes were removed before any water was collected for analysis. See Ross (1986) for the rationale of this piezometer flishing. The sampling bottles were

**Figure 5:** Illustrations of the Triple Tube Sampling Device and the Double Packer Sampling Device.


TRIPLE TUBE GAS DRIVE SAMPLER
0.6 cm teflon tubing
brass fitting
0.1 cm teflon tube (gas line)
Piezometer 1.0 cm polyethylene tubing
0.1 cm teflon tube (packer inflation line)
0.6 cm teflon tube
intake slots
2in
packer
wire
pack tip
DOUBLE PACKER SYSTEM PUMP
reinforced PVC tubing
wire cable
TOP PACKER
cable tie and wire
4.0 cm PVC tube
30 cm
32 cm x 6 cm Bic le Inner Tub
Piezometer 5.0 cm PVC tubing
packer inflation line
3.0 cm stainless steel tub
90 cm
inflatable bla de
Cable tie and wi
4.0 cm PVC tube
27 cm
32 cm x 6 cm Bic cle Inner Tub
BOTTOM PACKER
NOT TO SCALE

rinsed well with groundwater. Samples were collected in 60 ml hypovials and sealed with a teflon faced septum and crimped cap. The samples to be analyzed for aromatic hydrocarbons were injected with 0.2 ml of 10% sodium azide. Care was taken to avoid any headspace. Samples for chloride and TOC were collected in 20 ml bottles. All the samples were kept cool (4 C). The aromatic and chlorinated hydrocarbons dissolved in the groundwater were determined by a pentane extraction step followed by gas chromatography. The analyses are reported in parts per billion (ppb). The 20 ml samples were first analyzed for chloride content colorimetrically on a Technicon Autoanalyzer II. The samples were then acidified and purged for several minutes. The TOC content was analyzed on a Dohrmann Carbon Analyzer model DC-80, by a wet chemical oxidation with detection of resultant CO2. These analyses are reported in parts per million (ppm).

The construction of bundle piezometers is labour intensive and costly. Nine to eleven tubes of polyethylene must be measured and cut to a specific length. The ends of each tube must be slotted and wrapped in nytex screen. The tubes must then be arranged around a central tube of 1.2 cm PVC tube. The bore hole is dug with an auger and core samples are not collected. Because of the flexibility of the bundle, it is difficult to install in the auger hole. The polyethylene tubes commonly bow away from or twist around the central tube. Both occurrences result in a shortening of the final depth of the point.

Sampling the bundle piezometers with a triple tube sampler is a tedious time-consuming process. The sampler must be inserted to the bottom of each piezometer point. The deeper the point, the more difficult it becomes to insert, due to friction. The teflon tends to bend, the packers break off and because of the small diameter of the sampling tubes, they often become blocked with silt and sand. The packer must be deflated each time the well is flushed to allow the piezometer to recharge. On the average it takes four hours to sample one multilevel piezometer with nine points.

### 2.2 Sampling Fully-Screened Wells with a Double Packer Sampling Device

The double packer in situ pump consists of the commercially available I.E.A. sampling pump. The pump's bladder is encased in 90 cm of stainless steel tubing with a screened intake valve on either end and placed between two 27 cm inflatable packers. The packers are made of a 4 cm PVC pipe covered in a 32 cm x 6 cm piece of bicycle inner tube, connected to an inflation line. This assembly is attached to two tubes of reinforced, flexible PVC tubing, a wire cable and an inflation line 30 meters in length. The tubes are attached to the pump which controls the pumping rate. The pump is powered by a 12 volt battery. The packers were inflated to 100 psi. Nitrogen gas was used. When the pump bladder was relaxed, water flowed through the valves into the stainless steel tube. When the bladder was inflated, the valves shut and the water was forced up one of the PVC tubes. The bladder completed 3 to 4 cycles per minute with the water coming up the tube in pulses (Figure 5). In order to purge the water standing in the packered interval, atleast ten volumes of the stainless steel tube were removed before the sampling bottles were rinsed and a sample was collected. The samples were treated and analyzed by the same methods used for the triple tube samples.

The double packer was installed at three depths, 28 m,25 m and 22 m. The required length was measured from the bottom of the packer, along the reinforced tubing and marked. The whole assembly was lowered into the well, T-1, to the mark and secured with the wire cable. The first installation was on May 28th at 28m. The well was flushed and a sample was taken with the packers deflated. This was done to collect a sample representative of the average contaminant concentration over the length of the well. The packers were then inflated, the well flushed and a sample was taken. The well was sampled four more times at five minute intervals, each time flushing the well first. It became apparent that one of the packers was leaking. The packer assembly was removed from the well and one of the packers was torn. The packer was repaired and reinstalled at 28m on May 29th. Again, an initial sample was taken with the packers deflated. Five more samples were taken that day, four on the next day, two on June 3rd and one on June 10th. The adjacent multilevel piezometer ML-4b, point #4 at a depth of 27.9m was sampled using the triple tube sampler. On June 10th the packer assembly was pulled up to 25m. A sample was taken and the packers inflated. Two more samples were taken that day, two on June 12th, three on the 17th, five in the 19th and five on the 21st. Piezometer ML-4a points #6 and #7, at depths of 24.1m and 24.9m respectively, were sampled with the triple tube sampler. The packers were removed from the well.

On June 24th the packers were installed at 22m. Again an intial sample was taken with the packers deflated. Three more samples were taken that day, three on June 25rd and four on June 28th. The packers were removed from the well. On July 4th, ML-4a point #2 at 21m was sampled with the triple tube sampler.

The installation of open wells such as T-1 is more practical than the installation of bundle piezometers. The bore hole was dug with a 15 cm hollow auger. A 5 cm in diameter core sample was collected with a removable core tube. The collection of a core assists in defining the most permeable zones that should be sampled. The PVC tubing is lowered inside the auger, then the auger is carefully removed and the hole is left to backfill itself. If the packers effectively isolated a short interval sampling would be very simple after the initial setup. As the sampling at each interval is completed, the packers must just raised or lowered to the next interval of interest. The packers would only be deflated to move to the next interval. This should greatly reduce the sampling time and make the process of collecting water from different depths less tedious. The major drawback of this system would be the moving from one well to another. The double packer assembly and its sampling tubes are heavy and cumbersome to carry. It would be inconvienent to sample wells on sites where one could not get a vechile into. For both the triple tube and the double packer samplers one also needs a 12 volt battery and a nitrogen tank. Neither are very portable methods of sampling.

# Chapter III

# SUMMARY OF RESULTS

## 3.1 Leachate Input

During September and October, nine multilevel piezometers lying along the boundary of the landfill were sampled with the triple tube gas drive sampler. One piezometer lay to the west of the landfill (ML-62), one lay to the east (ML-01A) and the remainder lay along the southern edge. The only indication of contamination in ML-62 was a high TOC content in several points. ML-08, lying in the south west corner was also free of contaminants except TOC. The first indication of other contaminants occurs in ML-07, 70 meters from the southwest corner. Chloride levels significantly above the background level of 19.0 ppm (Ross,1986) are present in four of the top five points. Toluene is present in all the points, but is particularly high in the top two. Other aromatics such as chhlorobenzene, ethylbenzene, p-and-m-xylene and o-xylene first appear in ML-07 in low concentrations, below 15 ppb. Moving further west along piezometers ML-06 and ML-05, contaminant concentrations increase dramatically. Concentrations are at a maximum in piezometers ML-04 and ML-04A. Ml-01A, lying along the eastern edge has similar concentrations. The watertable at other piezometers along the eastern edge was below the screened interval of many points, precluding sample collection in these points.

Contaminant concentrations were compared by computer to determine correlation factors between various compounds. Correlation between chloride and TOC content was good, 87%. Toluene did not correlate well with chloride, but had a correlation factor of 97% with benzene. It correlated well with the other aromatic hydrocarbons, toluene vs. ethylbenzene 91%, toluene vs. p-and-m-xylene 83% and toluene vs. o-xylene 83%. The concentration of chlorinated hydrocarbons was low. They did not correlate with either chloride, or the aromatic hydrocarbons. The complete set of correlations is found in Appendix B. The concentration of the contaminants varies both horizontally and vertically. (See Figures 6,7 & 8).

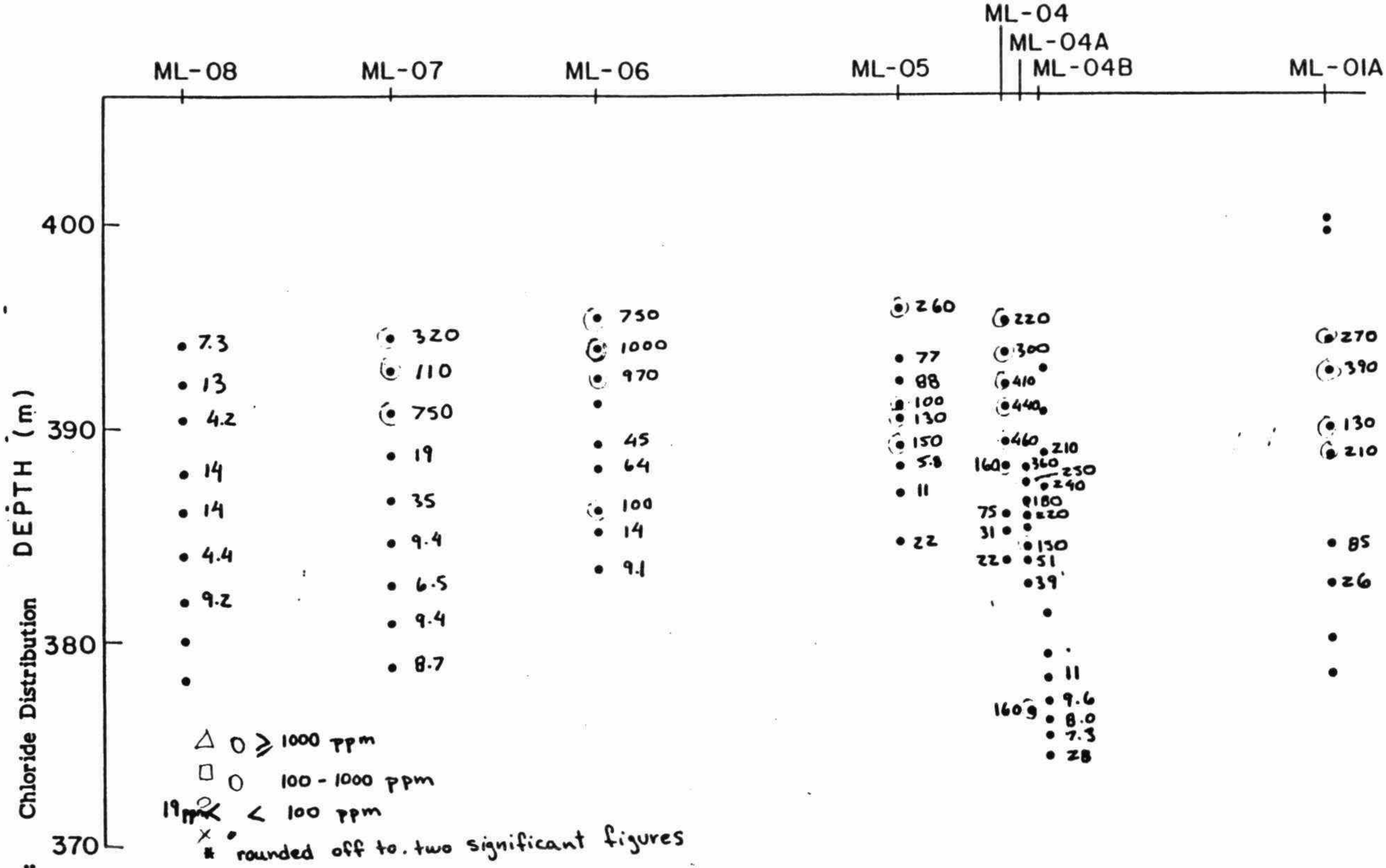


Figure 6: Chloride Distribution

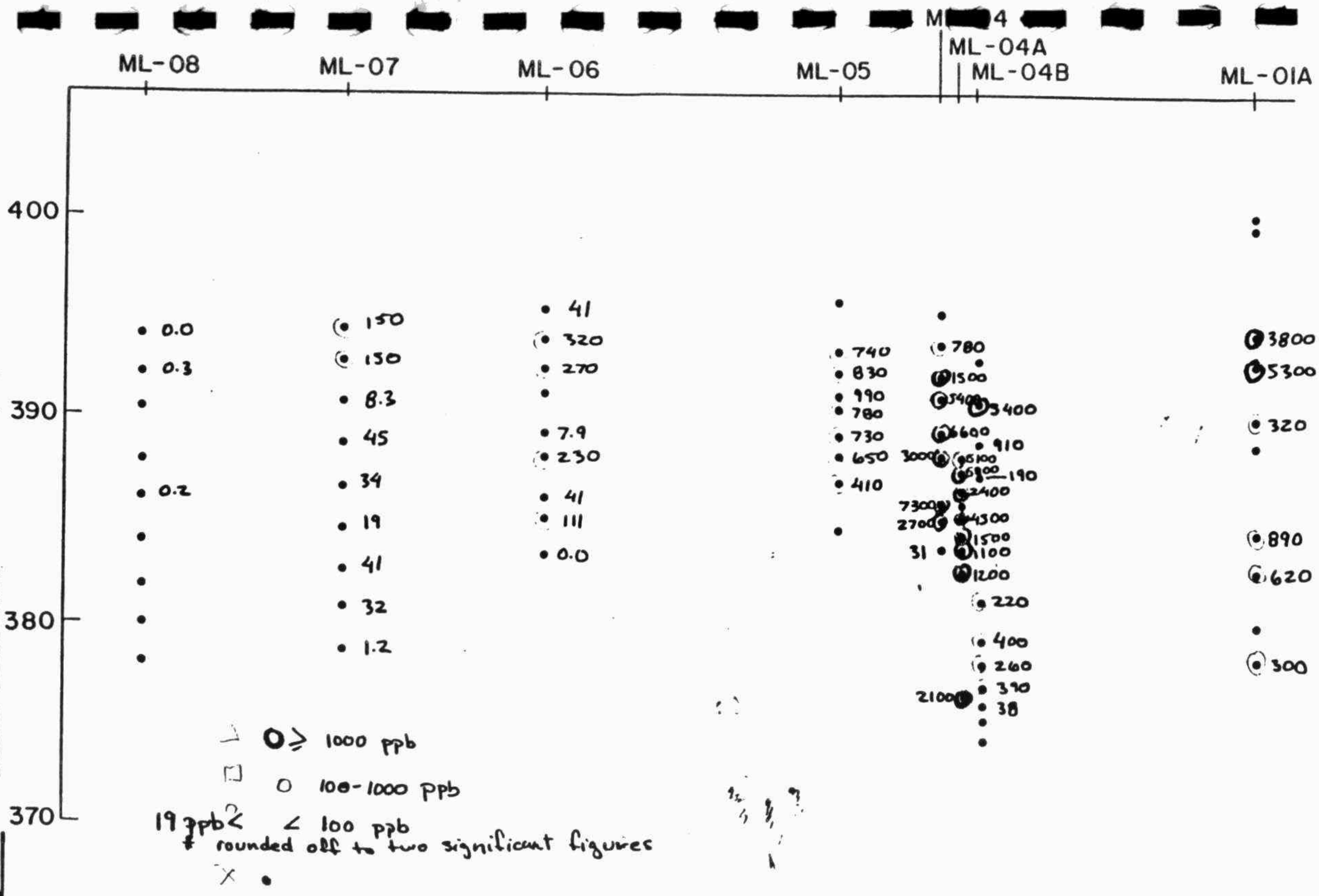


Figure 7: Toluene Distribution

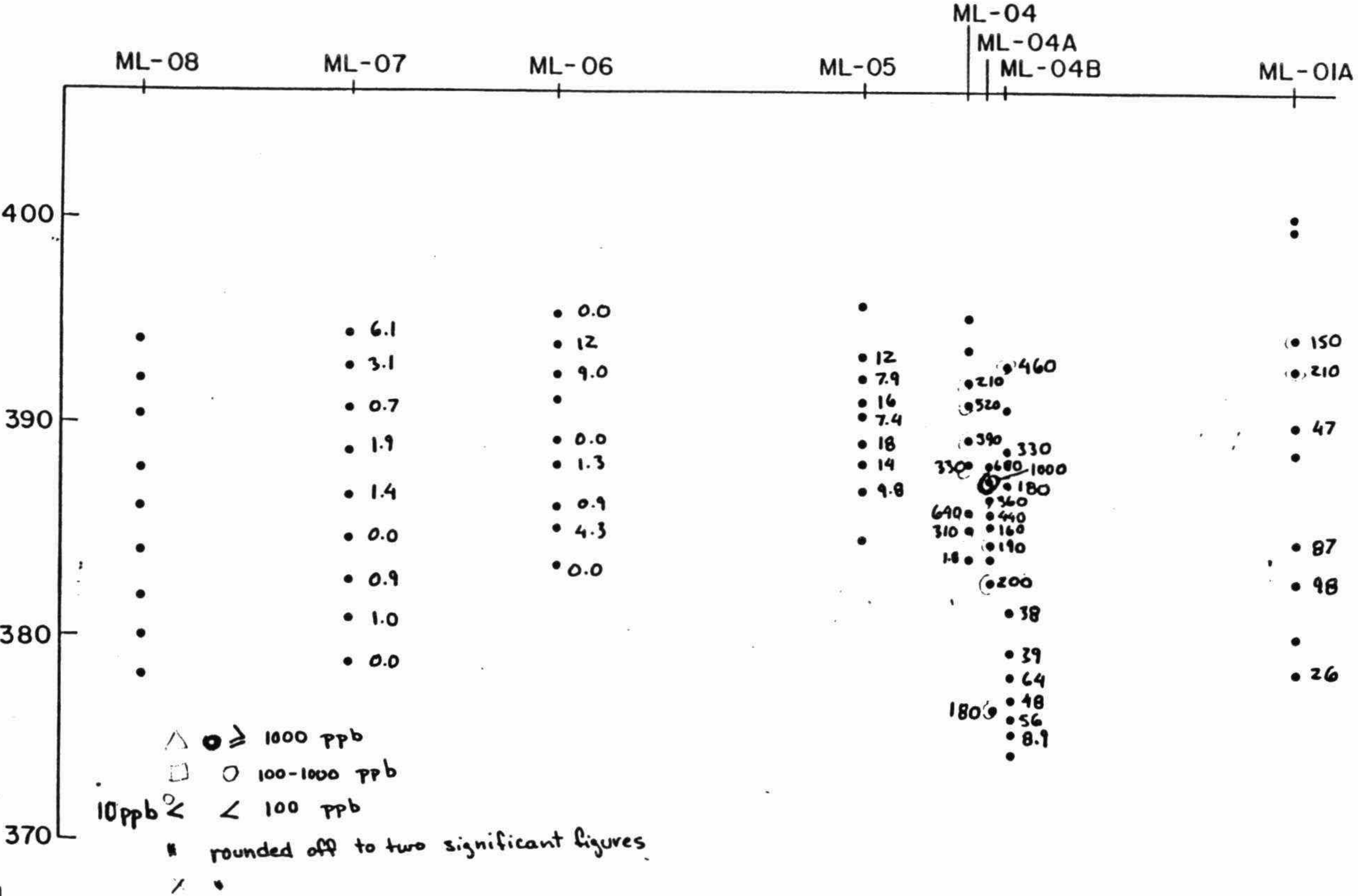


Figure 8: Ethylbenzene Distribution

## 3.2 Double-Packer Test

Piezometers ML4a and 4b were sampled twice. The first time (June 10 to July 4,1985) to compare with data from T-1 and the second time (Sept.17,1985) to compare with data from the other multilevel piezometers surrounding the landfill. Only selected points corresponding to the depth at which the double packer was installed were sampled the first time. The results of the analysis show a lower concentration of TOC, chloride, toluene, ethyl-benzene, p-and-m-xylene and o-xylene in ML-4b-4 and 4a-2 samples from the June and July sampling than in the Sept. sampling. Ml-4a-7 on the other hand had higher values. The difference in the values is probably a reflection of variation in the input from the landfill. The input appears to be very erratic in both concentration and distribution. However, both sets of data indicate that there are high levels of contaminants coming out of the landfill.

Samples from the first installation in T-1 at 28m were analyzed for TOC,chloride and chlorinated hydrocarbons. Only low concentration levels were detected. The initial sample, taken prior to inflation of the packers, does not differ from samples taken after inflation. The second installation at 28m produced similar results. The samples taken from the corresponding depth at ML-4b-4 have high levels of toluene,ethyl-benzene,p-and-m-xylene, and o-xylene. Though the agreement between samples taken at approximately the same time is poor, (50% variablity) the data indicate the presence of leachate at concentration levels much higher than those found in T-1 at the same depth.

The results show a different trend for the samples taken at 25m. The initial sample taken from T-1 shows very low concentrations. The second sample, taken after the packers were inflated had high levels of toluene, benzene, ethyl-benzene, p-and-m-xylene and o-xylene. In the third sample, taken 20 min. after inflation, the TOC and chloride content is also high. After 43 hours the levels began to drop. After five days the concentration levels had dropped down to the initial low levels. The data obtained from ML-4a-6 and-7 was considerably lower than the maximum concentrations reached in T-1, but did not fluctuate as radically.

The data from T-1 at 22m is similar to that for 28m. Contaminant concentrations were low initially and remained low. Comparative samples were collected from ML-4a-2 at a depth of 21m. The contaminants benzene, toluene, ethyl-benzene, p-and-m-xylene and o-xylene were present in high concentrations. TOC and chloride content was also high. The difference in depth of one meter can be significant. ML-4a-2 may not have been the best point to compare to T-1 22m, but it is obvious that there is a zone of high contaminant levels that the double packer samples are generally not indicating. The data is presented in Appendix C.

# Chapter IV

# CONCLUSIONS

## 4.1 Leachate-Input

Chloride is the first indication of contamination to appear. This was expected. Chloride is choosen as an indicator of leachate because it is highly mobile and is not susceptible to biological degradation. Chloride is often used together with TOC content as leachate indicators. Correlation between the two in other studies done this summer at Woolwich was poor. However, for this study the correlation between concentrations is good, with a correlation factor of 87%. In moving from relatively uncontaminated water to highly contaminated waters, toluene is the first aromatic hydrocarbon to be encountered. It does not correlate well with Chloride, however it does correlate well with the other aromatic hydrocarbons. Correlation among other aromatics was also good. This information indicates that the aromatic hydrocarbons tend to travel at the same rates. Chlorinated hydrocarbon concentrations were low. These did not correlate with either the chloride or the aromatic hydrocarbons.

Overall,the input from the landfill appears to be very irregular and complex. The concentration of the contaminants varies both horizontally and vertically. Pulses of high concentration are being sporadically released into the aquifer. This would explain some of the temporal variability seen in piezometers located downflow of the landfill. The correlation between the TOC and chloride content and between the various aromatics should be looked for in future studies.

## 4.2 Double Packer Test

The comparison of the results of the analyses done on both the open wells and the multilevel piezometers indicate that the double packer system did not effectively isolate the interval it enclosed. In three of the four tests run, the initial sample, taken while the packers were deflated, did not differ significantly from samples taken while the packers were inflated. Without the packers inflated the water collected would be an average of the water from the whole length of the screen. Inflating the packers does not change the concentration levels. Data from the multilevel piezometers indicates that the contaminant levels are high over the entire length sampled. It appears, therefore that, the water in well T-1 is being diluted by water below the contaminated zone. In some cases the packers did not provide a seal, but in others, the water must be flowing vertically in the disturbed sediments surrounding the well, during pumping. This is preventing isolation of the water flowing horizontally through the aquifer at the interval of interest. This report concludes that the double packer system is not capable of isolating one short interval of a well from another in this sand aquifer and is therefore not an accurate method of collecting samples when one is interested in contaminant concentrations at specific depths at the Woolwich Landfill Site.

## Chapter V

## SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

1. Neither higher initial concentrations of volatile organics in the standing water, nor any zones of higher contaminant concentrations were found. Conclusions can not be drawn on the possibility of volatile organics leaching from one zone to another through the piezometer tubing.

2. The contaminant concentrations in piezometer ML-16 were so low that is was not possible to distinguish between temporal variability and variability due to sampling and analysis techniques.

3. It is recommended that the study be repeated with a more contaminated piezometer.

4. Data obtained from the TOC and chloride analysis supports the idea that the standing water is enriched in contaminants.

5. It is recommended that a piezometer should be flushed at least three times before a sample is collected to obtain a representative sample of the groundwater in the aquifer.

6. Chloride is a more mobile contaminant than the hydrocarbons. It appears in high concentrations before other contaminants do.

7. There appears to be a good correlation between the increase in concentrations of different aromatic hydrocarbons. This correlation should be looked for in future studies.

8. Chloride and TOC appear to correlate well. Comparisons should be made with other studies.

9. The leachate input coming from the landfill is very complex and irregular in distribution and concentration. It is recommended that further sampling be carried out to gain a better understanding of the nature of the leachate input.

10. The double packer sampling system was not successful. It is recommended that the experiment be abandoned.

# Chapter VI

## ACKNOWLEDGEMENTS

I would like to thank Dr. J.F.Barker for guiding me through the writing of this report. I would like to thank Lloyd Lemon for his assistance in the field and on the computers. I would also like to thank Ralph Dickhout and Mike Houston for their time spent on the laboratory analyses. The drafting in this report is the work of Nadia Bahar.

# Appendix A

# DATA FROM PIEZOMETERS AROUND THE LANDFILL PERIMETER, 1985.

```
                       WOOLWICH LANDFILL SITE  - BOUNDARY SAMPLING

------------------------------- SITE=ML62 ---------------------------------

  OBS TUBE  DATE    TOC  CHLORIDE CHLOROFM TCETHANE CTETCL TCETHYL TETCETH

    1  1   20SEP85 51.3    10.3     0.0      1.1    0.3      0      0
    2  2   20SEP85  3.4    16.1     0.0      0.5    0.3      0      0
    3  3   20SEP85  1.4    14.5     1.4      0.0    4.2      0      0
    4  4   20SEP85  4.8    19.2     1.3      0.7    0.0      0      0
    5  5   20SEP85  6.8    15.6     0.0      0.2    0.8      0      0
    6  5   20SEP85   .       .      0.8      0.0    4.5      0      0
    7  5   20SEP85   .       .      0.0      0.2    0.3      0      0
    8  6   20SEP85  1.3    14.8     0.6      0.5    0.0      0      0
    9  7   20SEP85 87.6     7.2     0.0      0.6    0.3      0      0
   10  8   20SEP85  2.7      .      0.5      0.0    2.0      0      0

------------------------------- SITE=ML08 ---------------------------------

  OBS TUBE  DATE    TOC  CHLORIDE CHLOROFM TCETHANE CTETCL TCETHYL TETCET

   11    1  20SEP85  8.4     7.3    1.1      0.4    2.4    4.6      0
   12    2  20SEP85  8.1    13.0     .        .      .      .       .
   13    3  20SEP85  7.0     4.2    0.0      2.6    0.3    3.1      0
   14    4  20SEP85 56.1    14.4    0.0      0.0    2.3    1.8      0
   15    5  20SEP85 13.7    14.5    0.0      0.4    1.4    5.0      0
   16    5  20SEP85   .       .     0.0      0.0    0.8    3.9      0
   17    5  20SEP85   .       .     0.0      0.0    0.7    1.3      0
   18    6  20SEP85 39.4     4.4    0.8      0.2    0.8    2.9      0
   19    7  20SEP85 26.2     9.2    0.0      0.0    0.5    0.8      0

------------------------------- SITE=ML07 ---------------------------------

 OBS TUBE  DATE     TOC    CHLORIDE CHLOROFM TCETHANE CTETCL TCETHYL TETCE

 20    1  11SEP85 2564.0   314.5     0.0      1.8      0.4   14.9     0
 21    2  11SEP85  392.2   107.5     0.0      2.7      0.5   28.7     0
 22    3  11SEP85  269.1   751.0     4.5      0.0      2.0    9.7     0
 23    4  11SEP85   74.8    18.9     1.7      0.0      2.4   11.8     0
 24    5  11SEP85    6.6    34.8     0.2      0.8      0.3    3.3     0
 25    5  11SEP85     .       .      0.0      0.3      0.4    3.6     0
 26    5  11SEP85     .       .      3.0      1.4     15.0    4.2     0
 27    6  12SEP85   23.1     9.4     0.6      0.0      2.4    4.3     0
 28    7  12SEP85   10.0     6.5     2.1      0.4      2.5   11.7     0
 29    8  12SEP85    6.7     9.4     0.0      0.4      0.0    6.1     0
 30    9  12SEP85    4.3     8.7     0.0      1.1      2.2    1.5     0
```

```
                       WOOLWICH LANDFILL SITE  - BOUNDARY SAMPLING

------------------------------------ SITE=ML06 ------------------------------------

   OBS TUBE  DATE    TOC     CHLORIDE CHLOROFM TCETHANE CTETCL TCETHYL TETCETH

   31    1   16SEP85 5038.0   748.0      .         .       .       .       .
   32    2   16SEP85 6493.0  1037.0     3.0       0.1     0.0    20.8      0
   33    3   16SEP85 6416.0   972.0     2.5       0.6     0.0    36.9      0
   34    4   16SEP85     .       .      0.0       1.7     0.4     0.2      0
   35    5   16SEP85   11.9    45.3     0.0       0.0     0.4     0.5      0
   36    5   16SEP85     .       .      0.0       0.0     0.6     0.4      0
   37    5   16SEP85     .       .      0.0       0.0     2.0     0.4      0
   38    6   16SEP85   53.2    64.0     0.0       0.1     0.5     1.0      0
   39    7   16SEP85   32.2   102.3     0.0       0.0     2.3     4.4      0
   40    8   16SEP85    2.2    13.8     0.0       0.3     0.5     4.5      0
   41    9   16SEP85    4.8     9.1      .         .       .       .       .

------------------------------------ SITE=ML05 ------------------------------------

   OBS TUBE  DATE    TOC     CHLORIDE CHLOROFM TCETHANE CTETCL TCETHYL TETCETH

   42    1   16SEP85 1443.0   261.0      .         .       .       .       .
   43    2   16SEP85  427.1    77.3     0.3       0.4     2.1     1.5      0
   44    3   16SEP85  516.1    87.7     2.0       1.3     2.4     5.0      0
   45    4   16SEP85  669.9   104.9     0.0       1.5     0.0     2.3      0
   46    5   16SEP85  878.6   131.5     0.0       6.2     0.0     6.6      0
   47    5   16SEP85     .       .      0.5       6.5     0.0     6.9      0
   48    5   16SEP85     .       .      0.0       1.9     0.3     3.0      0
   49    6   16SEP85  903.6   146.0     0.4       4.3     0.0     5.5      0
   50    7   16SEP85 1049.0     5.8     0.0       1.1     0.4     2.8      0
   51    8   16SEP85 1016.0    11.2     0.0       1.4     2.1     4.4      0
   52    9   16SEP85   32.1    22.2      .         .       .       .       .

------------------------------------ SITE=ML04 ------------------------------------

   OBS TUBE  DATE    TOC     CHLORIDE CHLOROFM TCETHANE CTETCL TCETHYL TETCETH

   53    1   17SEP85 1678.0   218.5      .         .       .       .       .
   54    2   17SEP85 1963.0   298.5     1.9       0.4     0.0     0.8      0
   55    3   17SEP85 2272.0   413.0     0.0       0.5     0.0     4.7      0
   56    4   17SEP85 4918.0   435.0     0.0       0.2     0.4     7.2      0
   57    5   17SEP85 4819.0   458.0     0.0       0.4     0.3    16.6      0
   58    5   17SEP85     .       .      0.0       0.3     0.3    12.8      0
   59    5   17SEP85     .       .      0.0       0.3     0.7    13.1      0
   60    6   17SEP85  594.8   161.3     0.0       0.5     0.0     2.5      0
   61    7   17SEP85  347.2    75.5     0.0       1.2     0.4     3.4      0
   62    8   17SEP85  102.1    31.0     0.0       0.0     0.0     0.8      0
   63    9   17SEP85   54.7    22.0     0.0       0.6     0.0     1.4      0
```

```
                    WOOLWICH LANDFILL SITE  - BOUNDARY SAMPLING

------------------------------ SITE=ML4A ------------------------------------

OBS  TUBE   DATE     TOC     CHLORIDE  CHLOROFM  TCETHANE  CTETCL  TCETHYL  TETCETH

64    1   17SEP85  1876.0    364.0      0.0       0.0       2.0     12.4      0
65    2   17SEP85  1283.0    254.0      0.0       0.0       2.7      1.3      0
66    3   17SEP85   645.5    175.0      0.0       0.1       0.4      0.6      0
67    4   17SEP85   694.3    218.5       .         .         .        .       .
68    5   17SEP85  1070.0       .       3.4       0.0       2.0      1.2      0
69    5   17SEP85      .        .       0.0       0.5       0.0      1.2      0
70    5   17SEP85      .        .       3.4       0.0       2.5      1.4      0
71    6   17SEP85   483.9    146.5       .         .         .        .       .
72    7   17SEP85   205.7     50.6      0.0       0.0       0.5      0.7      0
73    8   17SEP85   123.5     38.7      0.0       0.0       2.8      1.2      0
74    9   17SEP85   463.1    159.5      0.0       0.4       2.8      1.4      0

------------------------------ SITE=ML4B ------------------------------------

OBS  TUBE   DATE     TOC     CHLORIDE  CHLOROFM  TCETHANE  CTETCL  TCETHYL  TETCETH

75    1   17SEP85   547.7    209.0       .         .         .        .       .
76    2   17SEP85  1038.0    240.5      0.0       0.3       1.3      0.7      0
77    4   17SEP85    66.4       .       0.0       0.3       1.2      1.1      0
78    5   17SEP85    79.8     10.6      0.0       0.0       1.3      0.4      0
79    5   17SEP85      .        .       0.0       0.0       1.3      0.1      0
80    5   17SEP85      .        .       0.0       0.0       4.9      0.3      0
81    6   17SEP85    88.5      9.6      0.0       0.0       1.3      0.2      0
82    7   17SEP85   141.8      8.0      0.1       0.0       1.1      0.6      0
83    8   17SEP85    82.9      7.3      0.0       0.0       0.3      0.0      0
84    9   17SEP85    76.3      7.5      1.5       0.0       1.9      0.2      0
85   10   17SEP85    67.7     27.8      1.5       0.2       2.5      0.0      0
86    0   17SEP85   902.7    172.5      0.0       0.2       1.8      0.7      0

------------------------------ SITE=ML1A ------------------------------------

OBS  TUBE   DATE     TOC     CHLORIDE  CHLOROFM  TCETHANE  CTETCL  TCETHYL  TETCET

87    3   20SEP85   727.3    270.5      0.0       1.0       0.5     13.1      0
88    4   20SEP85  1303.0    386.5      0.0       0.5       0.9     25.0      0
89    5   20SEP85   428.0    133.0      1.7       0.0       1.8      5.4      0
90    5   20SEP85      .        .       2.4       0.4       1.4      9.3      0
91    5   20SEP85      .        .       0.0       0.6       0.9     25.4      0
92    6   20SEP85  1038.0    205.5     19.9       0.0       1.1      8.7      0
93    7   20SEP85    22.6     85.0      0.0       0.4       1.5      7.6      0
94    8   20SEP85   109.0     26.1       .         .         .        .       .
95   11   20SEP85   241.0       .       0.0       0.5       0.6      0.9      0
```

```
                    WOOLWICH LANDFILL SITE  -  BOUNDARY SAMPLING

------------------------------- SITE=ML62 ----------------------------------

                                                         P
                           B       T                     M       O
                           E       O      C      E       X       X       C      T
                           N       L      L      T       Y       Y       U      M     N
         T        D        Z       U      B      B       L       L       M      B     A
   O     U        A        E       E      E      E       E       E       E      1     P
   B     B        T        N       N      N      N       N       N       N      2     T
   S     E        E        E       E      Z      Z       E       E       E      4     H

   1     1     20SEP85     0      4.4     0     0.7     0.0     0.5     0.0     0     0
   2     2     20SEP85     0      1.2     0     0.0     0.0     0.0     0.0     0     0
   3     3     20SEP85     0      1.9     0     0.0     0.0     0.0     0.0     0     0
   4     4     20SEP85     0      1.4     0     0.0     0.0     0.0     0.0     0     0
   5     5     20SEP85     0      5.6     0     0.0     0.8     0.0     0.0     0     0
   6     5     20SEP85     0      2.5     0     0.0     1.4     0.0     0.0     0     0
   7     5     20SEP85     0      1.8     0     0.0     0.0     0.0     0.6     0     0
   8     6     20SEP85     0      3.0     0     0.7     0.0     0.0     0.0     0     0
   9     7     20SEP85     1     10.8     0     1.0     0.8     0.0     0.0     0     0
  10     8     20SEP85     0      4.3     0     1.6     0.0     0.0     2.3     0     0

------------------------------- SITE=ML08 ----------------------------------

                                                         P
                           B       T                     M       O
                           E       O      C      E       X       X       C      T
                           N       L      L      T       Y       Y       U      M     N
         T        D        Z       U      B      B       L       L       M      B     A
   O     U        A        E       E      E      E       E       E       E      1     P
   B     B        T        N       N      N      N       N       N       N      2     T
   S     E        E        E       E      Z      Z       E       E       E      4     H

  11     1     20SEP85     0      0.0     0      0      0.0     0.0     0       0     0
  12     2     20SEP85     0      0.3     0      0      0.0     0.0     0       0     0
  13     3     20SEP85     .       .      .      .       .       .      .       .     .
  14     4     20SEP85     0      0.0     0      0      0.0    12.9     0       0     0
  15     5     20SEP85     0      0.2     0      0      5.1     0.0     0       0     0
  16     5     20SEP85     0      0.0     0      0      0.0     0.0     0       0     0
  17     5     20SEP85     .       .      .      .       .       .      .       .     .
  18     6     20SEP85     0      0.0     0      0      0.0     0.0     0       0     0
  19     7     20SEP85     0      0.0     0      0      0.0     0.0     0       0     0
```

## WOOLWICH LANDFILL SITE - BOUNDARY SAMPLING

```
------------------------------ SITE=WL07 ----------------------------------

                                                      P
                        B        T                    M         O
                        E        O        C      E    X         X       C     T
                        N        L        L      T    Y         Y       U     M      N
      T        D        Z        U        B      B    L         L       M     B      A
 O    U        A        E        E        E      E    E         E       E     1      P
 B    B        T        N        N        N      N    N         N       N     2      T
 S    E        E        E        E        Z      Z    E         E       E     4      H

20    1    11SEP85     3.9    154.4      2.2    6.1   15.2     11.4     0     0    11.7
21    2    11SEP85     4.4    146.8      1.4    3.1    7.8      3.4     0     0     0.0
22    3    11SEP85     0.0      8.3      0.0    0.7    1.5      0.0     0     0     0.[illegible]
23    4    11SEP85     1.5     44.5      0.0    1.9    3.8      1.6     0     0     0.[illegible]
24    5    11SEP85     2.3     72.4      0.0    2.7    6.3      3.4     0     0     0.0
25    5    11SEP85     1.4     33.8      0.0    1.4    3.0      1.8     0     0     0.[illegible]
26    5    11SEP85     0.0     15.8      0.0    0.0    0.0      0.0     0     0     0.[illegible]
27    6    12SEP85     0.0     18.6      0.0    0.0    2.7      1.4     0     0     0.0
28    7    12SEP85     1.7     41.0      0.0    0.9    4.1      2.2     0     0     0.0
29    8    12SEP85     1.4     31.7      0.0    1.0    4.1      1.6     0     0     0.[illegible]
30    9    12SEP85     0.0      1.2      0.0    0.0    0.0      0.0     0     0     0.0

------------------------------ SITE=WL06 ----------------------------------

                                                    P
                     B        T                     M         O
                     E        O       C     E       X         X
                     N        L       L     T       Y         Y       C      T
      T       D      Z        U       B     B       L         L       U      M      N
 O    U       A      E        E       E     E       E         E       M      B      A
 B    B       T      N        N       N     N       N         N       E      1      P
 S    E       E      E        E       Z     Z       E         E       N      2      T
                                                                      E      4      H

31    1    16SEP85  1.7     40.8     0     0.0     3.1      3.8     0.0    0.0    26.7
32    2    16SEP85  9.1    319.2     3    12.3    27.7     22.0     0.0    1.7    18.9
33    3    16SEP85  8.6    274.1     5     9.0    18.3     17.1     6.6    0.0    14.[illegible]
34    4    16SEP85   .        .      .      .       .        .       .      .       .
35    5    16SEP85  0.0      7.9     0     0.0     0.0      0.0     0.0    0.0     0.0
36    5    16SEP85  0.0      8.8     0     0.0     1.2      8.7     0.0    0.0     6.[illegible]
37    5    16SEP85   .        .      .      .       .        .       .      .       .
38    6    16SEP85  0.0    230.7     0     1.3     2.7      0.0     0.0    0.0     0.0
39    7    16SEP85  1.7     41.0     0     0.9     4.1      2.2     0.0    0.0     0.[illegible]
40    8    16SEP85  3.4    111.6     0     4.3     8.6      4.5     0.0    0.0     0.[illegible]
41    9    16SEP85  0.0      0.0     0     0.0     0.0      0.0     0.0    0.0     8.4
```

```
                    WOOLWICH LANDFILL SITE  -  BOUNDARY SAMPLING

------------------------------- SITE=ML05 ------------------------------------

                                                      P
                    B         T                       M       O
                    E         O      C       E        X       X     C    T
                    N         L      L       T        Y       Y     U    M     N
      T      D      Z         U      B       B        L       L     M    B     A
 O    U      A      E         E      E       E        E       E     E    1     P
 B    B      T      N         N      N       N        N       N     N    2     T
 S    E      E      E         E      Z       Z        E       E     E    4     H

42    1   16SEP85   .         .      .       .        .       .     .    .     .
43    2   16SEP85  5.9     734.6    0.0    11.8     35.3    16.5    0    0    0.0
44    3   16SEP85  9.5     831.6    0.0     7.9     28.2    13.2    0    0    0.0
45    4   16SEP85  8.2     931.4    0.0    16.3     48.4    20.6    0    0    0.0
46    5   16SEP85  0.0     777.9    0.0     0.0     28.4    12.0    0    0    0.0
47    5   16SEP85  4.1     446.3    0.0    18.4     73.7    37.1    0    0    0.0
48    5   16SEP85  9.6     909.2    0.0     7.4     21.1     9.6    0    0    1.4
49    6   16SEP85  8.2     734.5    0.0    18.1     74.2    35.2    0    0    2.2
50    7   16SEP85  7.2     651.8    0.4    13.8     47.3    21.5    0    0    0.0
51    8   16SEP85  3.3     412.6    0.0     9.8     35.4    18.2    0    0    1.6
52    9   16SEP85   .         .      .       .        .       .     .    .     .

------------------------------- SITE=ML04 ------------------------------------

                                                      P
                    B         T                       M       O
                    E         O      C       E        X       X     C    T
                    N         L      L       T        Y       Y     U    M     N
      T      D      Z         U      B       B        L       L     M    B     A
 O    U      A      E         E      E       E        E       E     E    1     P
 B    B      T      N         N      N       N        N       N     N    2     T
 S    E      E      E         E      Z       Z        E       E     E    4     H

53    1   17SEP85   .         .      .       .        .       .     .    .     .
54    2   17SEP85  0.0     777.8    0.0     0.0     28.4    12.0  0.0  0.0    0.0
55    3   17SEP85 11.1    1475.0    0.0   210.8     80.5    52.0  0.0  0.0   12.5
56    4   17SEP85 57.3    5381.0    5.1   523.7    396.1   207.1 11.9  0.0    6.7
57    5   17SEP85 70.1    7472.0    6.5   696.2    468.1   252.8 11.7  0.0   52.4
58    5   17SEP85 64.3    6593.0    5.7   588.2    395.3   211.2 15.1  2.6   52.4
59    5   17SEP85 19.8    2436.0    2.8   226.0    130.4    81.6  0.0  0.0   14.0
60    6   17SEP85 20.7    3037.0    0.0   332.1    115.3    65.1  0.0  0.0    0.0
61    7   17SEP85 55.1    7335.0    4.1   639.1    215.6   119.0  6.0  0.0    0.0
62    8   17SEP85 17.0    2654.0    0.0   312.1    109.2    59.5  0.0  0.0    0.0
63    9   17SEP85  0.0      31.2    0.0     1.8      3.3     0.0  0.0  0.0    0.0
```

```
                    WOOLWICH LANDFILL SITE  -  BOUNDARY SAMPLING

------------------------------------------ SITE=ML4A ------------------------------------------

                                                             P
                        B        T                           M         O
                        E        O       C         E         X         X      C     T
                        N        L       L         T         Y         Y      U     M    N
       T       D        Z        U       B         B         L         L      M     B
 O     U       A        E        E       E         E         E         E      E     1
 B     B       T        N        N       N         N         N         N      N     2    T
 S     E       E        E        E       Z         Z         E         E      E     4

64     1    17SEP85   39.0     5136     4.4     676.6     270.6     151.7     0    1.8   11.
65     2    17SEP85   40.0     5848     3.2    1048.0     234.8     137.6     0    0.0   2.
66     3    17SEP85   21.9     2361     0.0     364.5      74.9      39.2     0    0.0   0.
67     4    17SEP85      .        .       .         .         .         .     .      .   .
68     5    17SEP85   51.1     4887     1.8     482.6      96.0      48.4     0    2.7   0.
69     5    17SEP85   48.1     4540     0.0     444.7      92.1      46.9     0    2.7   0.
70     5    17SEP85   39.5     3639     1.6     362.9      84.5      44.3     0    2.0   0.
71     6    17SEP85   10.8     1490     0.0     160.4      42.4      21.5     0    0.0   0.
72     7    17SEP85    7.7     1060     0.0     188.4      41.7      21.3     0    0.0   0.
73     8    17SEP85    7.4     1182     0.0     201.7      47.6      26.0     0    0.0   0.
74     9    17SEP85   21.4     2089     3.2     184.0      72.5      46.4     0    0.0   0.

------------------------------------------ SITE=ML4B ------------------------------------------

                                                             P
                        B        T                           M         O
                        E        O       C         E         X         X      C     T
                        N        L       L         T         Y         Y      U     M    N
       T       D        Z        U       B         B         L         L      M     B    A
 O     U       A        E        E       E         E         E         E      E     1    P
 B     B       T        N        N       N         N         N         N      N     2    T
 S     E       E        E        E       Z         Z         E         E      E     4    H

75     1    17SEP85      .        .       .         .         .         .     .      .   .
76     2    17SEP85   59.1   5375.0       0     332.0      49.3      29.5   0.0    1.4   0
77     4    17SEP85    5.6    906.7       0     178.4      38.6      19.9   0.0    0.0   0
78     5    17SEP85    1.6    184.8       0      38.0       7.5       3.7   0.0    0.0   0
79     5    17SEP85      .        .       .         .         .         .     .      .   .
80     5    17SEP85    1.6    148.8       0      30.6       5.9       2.8   0.0    0.0   0
81     6    17SEP85    2.0    218.8       0      38.5       7.4       3.6   0.1    0.0   0
82     7    17SEP85    2.9    398.7       0      63.6      11.9       6.3   0.0    0.0   0
83     8    17SEP85    0.0    255.0       0      47.9      10.3       5.1   0.0    0.0   0
84     9    17SEP85    2.8    387.8       0      56.2      10.3       4.9   0.0    0.0   0
85    10    17SEP85    0.0     38.6       0       8.9       3.0       1.3   0.0    0.0   0
86     0    17SEP85   15.2   2526.0       0     463.4      82.6      44.7   0.0    0.0   0
```

```
                WOOLWICH LANDFILL SITE  -  BOUNDARY SAMPLING

--------------------------------- SITE=ML1A ---------------------------------

                                                       P
                         B         T                   M
                         E         O                   X         O
                         N         L         C    E    Y         X       C      T
             T           Z         U         L    T    L         Y       U      M     N
   O         U     D     E         E         B    B    E         L       M      B     A
   B         B     A     N         N         E    E    N         E       E      1     P
   S         E     T     E         E         N    N    E         N       N      2     T
                   E                         Z    Z              E       E      4     H

  87    3    20SEP85   17.7    3807.0     0   153.8   33.9    16.5    0.0    0    0.0
  88    4    20SEP85   45.3    5332.0     0   211.0   59.3    24.7    2.1    0    0.0
  89    5    20SEP85    2.0     219.6     0    47.0   14.9     7.9    0.0    0    5.5
  90    5    20SEP85    0.0     324.1     0    75.6   18.1    10.1    0.0    0    0.0
  91    5    20SEP85    0.0     361.9     0    73.2   22.2    12.0    1.1    0    0.0
  92    6    20SEP85     .         .      .      .       .       .      .     .     .
  93    7    20SEP85   10.0     885.5     0    87.1   21.8    10.5    0.0    0    0.0
  94    8    20SEP85    4.6     617.6     0    98.4    9.7     0.0    0.0    0    0.0
  95   11    20SEP85    6.5     301.1     0    26.0    6.5     4.8    0.0    0    0.0
```

## Appendix B

## CORRELATION OF SAMPLE PARAMETERS.

TOC - total organic carbon
Chlorofm - chloroform
Ctetcl - Carbon Tetrachloride
Tetceth - Tetrachloroethylene
Toluene - Toluene
Etbenz - Ethylbenzene
Oxylene - O-xylene
Tmb124 - 1,2,4-Trimethylbenzene

Chloride - Chloride
Tcethane - Trichloroethane
Tcethyl - Trichloroethylene
Benzene - Benzene
Clbenz - Chlorobenzene
Pmxylene - P-and-m-xylene
Cumene - Cumene
Napth - Napthalene

The first number is the coefficient of correlation.

The second number is a probability hypothesis condition.

The third number is the number of samples considered.

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                         WOOLWICH LANDFILL SITE  -  BOUNDARY SAMPLING

VARIABLE      N        MEAN       STD DEV          SUM      MINIMUM       MAXIMUM


TUBE         95     5.00000       2.39681      475.000            0      11.00000
DATE         95  9391.00000       2.58062   892145.000   9385.00000    9394.00000
TOC          76   779.08158    1411.16709    59210.200      1.30000    6493.00000
CHLORIDE     72   146.99306     216.89734    10583.500      4.20000    1037.00000
CHLOROFM     85     0.74235       2.32099       63.100            0      19.90000
TCETHANE     85     0.62941       1.14412       53.500            0       6.50000
CTETCL       85     1.28706       1.86093      109.400            0      15.00000
TCETHYL      85     4.87882       7.04391      414.700            0      36.90000
TETCETH      85           0             0            0            0             0
BENZENE      84    10.44405      17.41795      877.300            0      70.10000
TOLUENE      84  1188.60595    1925.34931    99842.900            0    7472.00000
CLBENZ       84     0.60000       1.47982       50.400            0       6.50000
ETBENZ       84   116.98214     206.09887     9826.500            0    1048.00000
PMXYLENE     84    46.74762      88.75625     3926.800            0     468.10000
OXYLENE      84    25.40833      48.19765     2134.300            0     252.80000
CUMENE       84     0.68452       2.59283       57.500            0      15.10000
TMB124       84     0.17738       0.60904       14.900            0       2.70000
NAPTH        84     2.98571       9.09384      250.800            0      52.40000
```

```
                    WOOLWICH LANDFILL SITE   -  BOUNDARY SAMPLING

  CORRELATION COEFFICIENTS / PROB > |R| UNDER HO:RHO=0
 / NUMBER OF OBSERVATIONS

              TUBE       DATE         TOC CHLORIDE CHLOROFM TCETHANE   CTETCL

TUBE       1.00000   0.00688 -0.37609 -0.44732 -0.01837 -0.08267  0.01226
            0.0000    0.9472   0.0008   0.0001   0.8675   0.4519   0.9113
                95        95       76       72       85       85       85

DATE       0.00688   1.00000 -0.11661 -0.16362  0.02752 -0.17556 -0.19355
            0.9472    0.0000   0.3158   0.1696   0.8026   0.1080   0.0759
                95        95       76       72       85       85       85

TOC       -0.37609 -0.11661  1.00000  0.87258  0.11946  0.02798 -0.26791
            0.0008   0.3158   0.0000   0.0001   0.3394   0.8236   0.0296
                76       76       76       72       66       66       66

CHLORIDE -0.44732 -0.16362  0.87258  1.00000  0.21058 -0.03720 -0.18301
           0.0001   0.1696   0.0001   0.0000   0.1004   0.7741   0.1545
               72       72       72       72       62       62       62

CHLOROFM -0.01837  0.02752  0.11946  0.21058  1.00000 -0.09502  0.14643
           0.8675   0.8026   0.3394   0.1004   0.0000   0.3870   0.1811
               85       85       66       62       85       85       85

TCETHANE -0.08267 -0.17556  0.02798 -0.03720 -0.09502  1.00000 -0.12960
           0.4519   0.1080   0.8236   0.7741   0.3870   0.0000   0.2372
               85       85       66       62       85       85       85

CTETCL    0.01226 -0.19355 -0.26791 -0.18301  0.14643 -0.12960  1.00000
           0.9113   0.0759   0.0296   0.1545   0.1811   0.2372   0.0000
               85       85       66       62       85       85       85

TCETHYL  -0.27379 -0.19926  0.63567  0.67817  0.13817  0.16205 -0.10860
           0.0112   0.0675   0.0001   0.0001   0.2073   0.1384   0.3225
               85       85       66       62       85       85       85

TETCETH   0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
           1.0000   1.0000   1.0000   1.0000   1.0000   1.0000   1.0000
               85       85       66       62       85       85       85

BENZENE  -0.15064  0.03528  0.40142  0.32773 -0.05186 -0.08385 -0.10391
           0.1714   0.7500   0.0006   0.0077   0.6499   0.4625   0.3621
               84       84       69       65       79       79       79

TOLUENE  -0.16454  0.07191  0.32314  0.27152 -0.10811 -0.06662 -0.10490
           0.1347   0.5157   0.0068   0.0287   0.3430   0.5597   0.3575
               84       84       69       65       79       79       79

CLBENZ   -0.16843 -0.08212  0.68647  0.53840  0.04593 -0.05530 -0.09248
           0.1256   0.4577   0.0001   0.0001   0.6877   0.6284   0.4176
               84       84       69       65       79       79       79

ETBENZ   -0.17842  0.05846  0.26933  0.21675 -0.11326 -0.15913 -0.04600
           0.1044   0.5973   0.0252   0.0829   0.3203   0.1613   0.6873
               84       84       69       65       79       79       79
```

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                    WOOLWICH LANDFILL SITE  -  BOUNDARY SAMPLING                    1

  CORRELATION COEFFICIENTS / PROB > |R| UNDER HO:RHO=0
 / NUMBER OF OBSERVATIONS

                  TUBE       DATE         TOC  CHLORIDE CHLOROFM TCETHANE    CTETCL

 PMXYLENE -0.12818    0.00403    0.47262    0.29599 -0.14932 -0.00964 -0.12268
            0.2453     0.9710     0.0001     0.0167   0.1890   0.9328   0.2815
                84         84         69         65       79       79       79

 OXYLENE  -0.13907    0.00270    0.48674    0.31571 -0.15050 -0.02763 -0.11792
            0.2071     0.9805     0.0001     0.0104   0.1855   0.8090   0.3007
                84         84         69         65       79       79       79

 CUMENE   -0.03080    0.02625    0.58030    0.37888 -0.06555 -0.04687 -0.13100
            0.7809     0.8126     0.0001     0.0019   0.5660   0.6817   0.2498
                84         84         69         65       79       79       79

 TMB124   -0.15379   -0.00601    0.27775    0.40635  0.26176 -0.11661 -0.03129
            0.1625     0.9567     0.0208     0.0008   0.0198   0.3061   0.7843
                84         84         69         65       79       79       79

 NAPTH    -0.17725   -0.05913    0.75371    0.60243 -0.01554 -0.04941 -0.13773
            0.1067     0.5931     0.0001     0.0001   0.8919   0.6655   0.2261
                84         84         69         65       79       79       79

               TCETHYL    TETCETH    BENZENE   TOLUENE   CLBENZ   ETBENZ PMXYLENE


 TUBE     -0.27379    0.00000   -0.15064  -0.16454 -0.16843 -0.17842 -0.12818
            0.0112     1.0000     0.1714    0.1347   0.1256   0.1044   0.2453
                85         85         84        84       84       84       84

 DATE     -0.19926    0.00000    0.03528   0.07191 -0.08212  0.05846  0.00403
            0.0675     1.0000     0.7500    0.5157   0.4577   0.5973   0.9710
                85         85         84        84       84       84       84

 TOC       0.63567    0.00000    0.40142   0.32314  0.68647  0.26933  0.47262
            0.0001     1.0000     0.0006    0.0068   0.0001   0.0252   0.0001
                66         66         69        69       69       69       69

 CHLORIDE  0.67817    0.00000    0.32773   0.27152  0.53840  0.21675  0.29599
            0.0001     1.0000     0.0077    0.0287   0.0001   0.0829   0.0167
                62         62         65        65       65       65       65

 CHLOROFM  0.13817    0.00000   -0.05186  -0.10811  0.04593 -0.11326 -0.14932
            0.2073     1.0000     0.6499    0.3430   0.6877   0.3203   0.1890
                85         85         79        79       79       79       79

 TCETHANE  0.16205    0.00000   -0.08385  -0.06662 -0.05530 -0.15913 -0.00964
            0.1384     1.0000     0.4625    0.5597   0.6284   0.1613   0.9328
                85         85         79        79       79       79       79

 CTETCL   -0.10860    0.00000   -0.10391  -0.10490 -0.09248 -0.04600 -0.12268
            0.3225     1.0000     0.3621    0.3575   0.4176   0.6873   0.2815
                85         85         79        79       79       79       79
```

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                          WOOLWICH LANDFILL SITE   -  BOUNDARY SAMPLING

   CORRELATION COEFFICIENTS / PROB > |R| UNDER H0:RHO=0
  / NUMBER OF OBSERVATIONS

              TCETHYL    TETCETH    BENZENE    TOLUENE     CLBENZ     ETBENZ  PMXYLENE

 TCETHYL      1.00000    0.00000    0.18593    0.16435    0.46875    0.05576    0.20053
               0.0000     1.0000     0.1009     0.1478     0.0001     0.6255     0.0764
                   85         85         79         79         79         79         79

 TETCETH      0.00000    0.00000    0.00000    0.00000    0.00000    0.00000    0.00000
               1.0000     1.0000     1.0000     1.0000     1.0000     1.0000     1.0000
                   85         85         79         79         79         79         79

 BENZENE      0.18593    0.00000    1.00000    0.97120    0.69205    0.86095    0.83848
               0.1009     1.0000     0.0000     0.0001     0.0001     0.0001     0.0001
                   79         79         84         84         84         84         84

 TOLUENE      0.16435    0.00000    0.97120    1.00000    0.66106    0.91160    0.84626
               0.1478     1.0000     0.0001     0.0000     0.0001     0.0001     0.0001
                   79         79         84         84         84         84         84

 CLBENZ       0.46875    0.00000    0.69205    0.66106    1.00000    0.64707    0.81905
               0.0001     1.0000     0.0001     0.0001     0.0000     0.0001     0.0001
                   79         79         84         84         84         84         84

 ETBENZ       0.05576    0.00000    0.86095    0.91160    0.64707    1.00000    0.83625
               0.6255     1.0000     0.0001     0.0001     0.0001     0.0000     0.0001
                   79         79         84         84         84         84         84

 PMXYLENE     0.20053    0.00000    0.83848    0.84626    0.81905    0.83625    1.00000
               0.0764     1.0000     0.0001     0.0001     0.0001     0.0001     0.0000
                   79         79         84         84         84         84         84

 OXYLENE      0.20718    0.00000    0.83329    0.84316    0.83503    0.84481    0.99724
               0.0669     1.0000     0.0001     0.0001     0.0001     0.0001     0.0001
                   79         79         84         84         84         84         84

 CUMENE       0.34970    0.00000    0.62830    0.57950    0.77217    0.47252    0.78717
               0.0016     1.0000     0.0001     0.0001     0.0001     0.0001     0.0001
                   79         79         84         84         84         84         84

 TMB124       0.07254    0.00000    0.59833    0.50834    0.36040    0.45299    0.35913
               0.5252     1.0000     0.0001     0.0001     0.0008     0.0001     0.0008
                   79         79         84         84         84         84         84

 NAPTH        0.40779    0.00000    0.47501    0.42809    0.69733    0.37725    0.65948
               0.0002     1.0000     0.0001     0.0001     0.0001     0.0004     0.0001
                   79         79         84         84         84         84         84

              OXYLENE     CUMENE     TMB124      NAPTH


 TUBE        -0.13907   -0.03080   -0.15379   -0.17725
               0.2071     0.7809     0.1625     0.1067
                   84         84         84         84
```

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                       WOOLWICH LANDFILL SITE   -  BOUNDARY SAMPLING

   CORRELATION COEFFICIENTS / PROB > |R| UNDER HO:RHO=0
  / NUMBER OF OBSERVATIONS

              OXYLENE    CUMENE    TMB124     NAPTH

   DATE       0.00270   0.02625  -0.00601  -0.05913
               0.9805    0.8126    0.9567    0.5931
                   84        84        84        84

   TOC        0.48674   0.58030   0.27775   0.75371
               0.0001    0.0001    0.0208    0.0001
                   69        69        69        69

   CHLORIDE   0.31571   0.37888   0.40635   0.60243
               0.0104    0.0019    0.0008    0.0001
                   65        65        65        65

   CHLOROFM  -0.15050  -0.06555   0.26176  -0.01554
               0.1855    0.5660    0.0198    0.8919
                   79        79        79        79

   TCETHANE  -0.02763  -0.04687  -0.11661  -0.04941
               0.8090    0.6817    0.3061    0.6655
                   79        79        79        79

   CTETCL    -0.11792  -0.13100  -0.03129  -0.13773
               0.3007    0.2498    0.7843    0.2261
                   79        79        79        79

   TCETHYL    0.20718   0.34970   0.07254   0.40779
               0.0669    0.0016    0.5252    0.0002
                   79        79        79        79

   TETCETH    0.00000   0.00000   0.00000   0.00000
               1.0000    1.0000    1.0000    1.0000
                   79        79        79        79

   BENZENE    0.83329   0.62830   0.59833   0.47501
               0.0001    0.0001    0.0001    0.0001
                   84        84        84        84

   TOLUENE    0.84316   0.57950   0.50834   0.42809
               0.0001    0.0001    0.0001    0.0001
                   84        84        84        84

   CLBENZ     0.83503   0.77217   0.36040   0.69733
               0.0001    0.0001    0.0008    0.0001
                   84        84        84        84

   ETBENZ     0.84481   0.47252   0.45299   0.37725
               0.0001    0.0001    0.0001    0.0004
                   84        84        84        84

   PXYLENE    0.99724   0.78717   0.35913   0.65948
               0.0001    0.0001    0.0008    0.0001
                   84        84        84        84
```

```
                     WOOLWICH LANDFILL SITE   -  BOUNDARY SAMPLING

 CORRELATION COEFFICIENTS / PROB > |R| UNDER HO:RHO=0
/ NUMBER OF OBSERVATIONS

             OXYLENE    CUMENE     TMB124      NAPTH

OXYLENE      1.00000    0.77539    0.35635    0.67011
              0.0000     0.0001     0.0009     0.0001
                  84         84         84         84

CUMENE       0.77539    1.00000    0.22172    0.72050
              0.0001     0.0000     0.0427     0.0001
                  84         84         84         84

TMB124       0.35635    0.22172    1.00000    0.31922
              0.0009     0.0427     0.0000     0.0031
                  84         84         84         84

NAPTH        0.67011    0.72050    0.31922    1.00000
              0.0001     0.0001     0.0031     0.0000
                  84         84         84         84
```

## Appendix C

## DATA FROM THE DOUBLE PACKER EXPERIMENT, 1985

### WOOLWICH DOUBLE PACKER TEST
### WELL: T1 DEPTH: 27M DATE: MAY 28, 1985

| OBS | TIME | TOC | CL | CHLORFM | TCHLETHA | CARTET | TCLETHYL |
|---|---|---|---|---|---|---|---|
| 1 | 0.000 | 2.4 | 14.7 | 0 | 0.28 | 0 | 0 |
| 2 | 0.083 | 2.6 | 14.5 | 0 | 0.27 | 0 | 0 |
| 3 | 0.167 | 2.4 | 14.0 | 0 | 0.27 | 0 | 0 |
| 4 | 0.250 | 5.3 | 14.2 | 0 | 0.25 | 0 | 0 |
| 5 | 0.333 | 2.6 | 14.1 | 0 | 0.24 | 0 | 0 |
| 6 | 0.833 | 2.4 | 14.4 | 0 | 0.26 | 0 | 0 |

### WOOLWICH DOUBLE PACKER TEST
### WELL: T1 DEPTH: 27M DATE: MAY 29 TO JUNE 10, 1985

| OBS | TIME | BENZENE | TOLUENE | CLBENZ | ETBENZ | PMXYLENE | OXYLENE | CUMENE | TMB124 | NAPTH |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000 | . | . | . | . | . | . | . | . | . |
| 2 | 0.167 | . | . | . | . | . | . | . | . | . |
| 3 | 0.250 | . | . | . | . | . | . | . | . | . |
| 4 | 0.750 | . | . | . | . | . | . | . | . | . |
| 5 | 4.167 | . | . | . | . | . | . | . | . | . |
| 6 | 4.250 | . | . | . | . | . | . | . | . | . |
| 7 | 22.750 | . | . | . | . | . | . | . | . | . |
| 8 | 22.833 | . | . | . | . | . | . | . | . | . |
| 9 | 26.000 | . | . | . | . | . | . | . | . | . |
| 10 | 26.083 | . | . | . | . | . | . | . | . | . |
| 11 | 118.917 | . | . | . | . | . | . | . | . | . |
| 12 | 119.000 | . | . | . | . | . | . | . | . | . |
| 13 | 287.750 | 3.3 | 2.0 | 0 | 0 | 0 | 0 | 0.0 | 0 | 0.45 |
| 14 | 287.750 | 2.8 | 2.1 | 0 | 0 | 0 | 0 | 20.3 | 0 | 0.[illegible] |

### WOOLWICH DOUBLE PACKER TEST
### WELL: T1 DEPTH: 27M DATE: MAY 29 TO JUNE 10, 1985

| OBS | TIME | TOC | CL | CHLORFM | TCHLETHA | CARTET | TCLETHYL | PER |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.000 | 2.4 | 13.8 | 0 | 0.00 | 0 | 0.0 | 0 |
| 2 | 0.167 | 2.6 | 13.8 | 0 | 0.00 | 0 | 0.0 | 0 |
| 3 | 0.250 | 20.8 | 13.8 | 0 | 0.00 | 0 | 0.0 | 0 |
| 4 | 0.750 | 3.3 | 13.3 | 0 | 0.00 | 0 | 0.0 | 0 |
| 5 | 4.167 | 2.4 | 13.8 | 0 | 0.00 | 0 | 0.0 | 0 |
| 6 | 4.250 | 2.9 | 13.3 | 0 | 0.00 | 0 | 0.0 | 0 |
| 7 | 22.750 | 3.2 | 12.6 | 0 | 0.13 | 0 | 0.0 | 0 |
| 8 | 22.833 | 2.9 | 14.5 | 0 | 0.17 | 0 | 0.7 | 0 |
| 9 | 26.000 | 2.9 | 14.0 | 0 | 0.12 | 0 | 0.0 | 0 |
| 10 | 26.083 | 2.6 | 13.6 | 0 | 0.12 | 0 | 0.0 | 0 |
| 11 | 118.917 | 2.6 | 13.8 | 0 | 0.14 | 0 | 0.0 | 0 |
| 12 | 119.000 | 2.3 | 13.8 | 0 | 0.16 | 0 | 0.0 | 0 |
| 13 | 287.750 | . | . | 0 | 0.00 | 0 | 0.0 | 0 |
| 14 | 287.750 | . | . | . | . | . | . | . |

```
                         WOOLWICH DOUBLE PACKER TEST
              WELL: T1  DEPTH: 25M  DATE: JUNE 10 TO JUNE 21, 1985

OBS     TIME BENZENE TOLUENE CLBENZ ETBENZ PMXYLENE OXYLENE CUMENE TMB124 NAPTH

  1    0.000    2.50      3.2  0.00     0.00      0.0      0.0     0.0     3.0   10.5
  2    0.167   39.50   1442.8  0.00   610.50     91.5     49.5     0.0     1.6    7.7
  3    0.333   39.10   1327.1  0.00   507.20     75.3     41.7     9.9     2.3    6.4
  4   43.250   13.60    204.3  0.00    72.80      0.0      5.6     0.0     0.0    3.1
  5   43.333    2.00     48.8  0.00    92.60      2.5      1.2     0.0     0.0    9.1
  6  163.250    2.40      3.7  0.00    11.90      2.5      1.1     0.0     1.2   11.4
  7  163.333    0.82     21.5  0.00     5.60      1.4      0.0     0.0     0.0    4.5
  8  210.250    2.90     22.3  0.00     7.00      0.0      0.0     0.0     2.3    1.5
  9  210.500    3.10     20.1  0.00     5.50      0.0      0.0     0.0     0.0    5.7
 10  211.750    2.30     13.7  0.91     5.90      0.0      0.0     0.0     0.0    6.7
 11  213.250    3.20     16.6  0.00     4.60      0.0      0.0     0.0     0.0    4.6
 12  261.250    0.00     15.4  0.00     5.30      0.0      3.0     0.0     0.0    0.7
 13  261.250    0.00     16.7  0.00     5.07      0.0      3.3     0.0     0.0    0.8
 14  261.250    1.10     13.4  2.20     3.50      0.8      2.0     0.0     0.0    2.5
 15  262.250    3.20     13.9  0.00     4.40      0.0      0.0     0.0     0.0    2.6
 16  262.250    2.10     13.9  0.00     3.30      0.0      0.0     0.0     0.0    0.6
```

```
                         WOOLWICH DOUBLE PACKER TEST
              WELL: T1  DEPTH: 25M  DATE: JUNE 10 TO JUNE 21, 1985

OBS       TIME      TOC       CL     CHLORFM    TCHLETHA    CARTET    TCLETHYL    PER

  1      0.000       .         .       0.00         0          0          0        0
  2      0.167      7.3      14.2      0.24         0          0          0        0
  3      0.333   1273.0     229.0      0.25         0          0          0        0
  4     43.250   1364.0     218.0      0.00         0          0          0        0
  5     43.333    298.3      93.0      0.00         0          0          0        0
  6    163.250     10.2      13.1      0.00         0          0          0        0
  7    163.333      8.9      13.1      0.00         0          0          0        0
  8    210.250     13.8      15.2      0.00         0          0          0        0
  9    210.500      9.3      12.5      0.00         0          0          0        0
 10    211.750     13.6      12.5      0.00         0          0          0        0
 11    213.250      8.0      12.5      0.00         0          0          0        0
 12    261.250      9.9      12.5      0.00         0          0          0        0
 13    261.250       .         .        .           .          .          .        .
 14    261.250       .         .        .           .          .          .        .
 15    262.250      8.5      12.5      0.00         0          0          0        0
 16    262.250       .         .        .           .          .          .        .
```

## WOOLWICH DOUBLE PACKER TEST
## WELL: T1 DEPTH: 22M DATE: JUNE 24 TO JUNE 28, 1985

| OBS | TIME | BENZENE | TOLUENE | CLBENZ | ETBENZ | PMXYLENE | OXYLENE | CUMENE | TMB124 | NAPT |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.000 | 1.9 | 19.5 | 0.0 | 6.1 | 0.00 | 2.2 | 0.0 | 0.00 | [illegible] |
| 2 | 0.000 | 1.3 | 19.3 | 0.0 | 5.5 | 0.00 | 1.5 | 0.0 | 0.00 | [illegible] |
| 3 | 0.250 | 4.4 | 26.7 | 0.1 | 0.8 | 0.00 | 1.5 | 0.0 | 0.00 | 0.0 |
| 4 | 0.250 | 0.0 | 23.4 | 0.0 | 8.9 | 1.40 | 2.8 | 0.0 | 0.00 | [illegible] |
| 5 | 0.500 | 0.0 | 19.0 | 0.0 | 6.8 | 0.00 | 2.1 | 0.0 | 0.00 | [illegible] |
| 6 | 0.500 | 2.9 | 16.5 | 0.0 | 6.8 | 0.00 | 8.8 | 0.0 | 0.00 | 0.0 |
| 7 | 1.000 | 13.7 | 0.0 | 4.9 | 0.7 | 2.50 | 3.6 | 0.0 | 0.00 | 0.0 |
| 8 | 25.750 | 0.0 | 25.1 | 0.0 | 12.3 | 1.95 | 5.5 | 0.0 | 0.00 | [illegible] |
| 9 | 26.167 | 0.0 | 16.9 | 0.0 | 5.9 | 0.00 | 1.7 | 0.0 | 0.00 | 0.0 |
| 10 | 93.500 | 0.0 | 15.2 | 0.0 | 4.6 | 0.00 | 1.6 | 0.0 | 0.00 | 0.0 |
| 11 | 93.750 | 1.3 | 14.4 | 0.0 | 4.7 | 1.20 | 5.2 | 1.3 | 0.51 | [illegible] |
| 12 | 95.000 | 0.0 | 15.5 | 0.0 | 5.2 | 0.00 | 1.8 | 0.0 | 0.00 | [illegible] |
| 13 | 239.000 | 1.4 | 25.5 | 0.0 | 6.9 | 0.00 | 2.1 | 0.0 | 0.00 | 2.0 |
| 14 | 239.000 | 1.3 | 22.2 | 0.0 | 6.1 | 0.00 | 1.6 | 0.0 | 0.00 | [illegible] |
| 15 | 239.000 | 1.6 | 24.0 | 0.0 | 7.4 | 0.00 | 1.6 | 0.0 | 0.00 | [illegible] |
| 16 | 240.000 | 0.0 | 21.5 | 0.0 | 6.0 | 1.40 | 1.4 | 0.0 | 0.00 | 0.0 |

## WOOLWICH DOUBLE PACKER TEST
## WELL: T1 DEPTH: 22M DATE: JUNE 24 TO JUNE 28, 1985

| OBS | TIME | TOC | CL | CHLORFM | TCHLETHA | CARTET | TCLETHYL | [illegible] |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.000 | 18.900 | 15.300 | 0.00 | 0.00 | 0.00 | 0.0 | 0. |
| 2 | 0.000 | . | . | 0.00 | 0.00 | 0.00 | 0.0 | 0. |
| 3 | 0.250 | 9.800 | 15.600 | 0.00 | 0.00 | 0.00 | 0.0 | 0. |
| 4 | 0.250 | . | . | 0.00 | 0.00 | 0.00 | 0.0 | 0. |
| 5 | 0.500 | 10.700 | 15.600 | 0.00 | 0.00 | 0.00 | 0.0 | 0. |
| 6 | 0.500 | . | 1.000 | 0.00 | 0.00 | 0.00 | 0.0 | . |
| 7 | 1.000 | . | 25.667 | 0.00 | 0.00 | 0.00 | 0.0 | . |
| 8 | 25.750 | 12.400 | 15.400 | 0.00 | 0.00 | 0.00 | 0.0 | 0. |
| 9 | 26.167 | 8.300 | 14.100 | 0.00 | 0.00 | 0.00 | 0.0 | 0. |
| 10 | 93.500 | 7.800 | 15.200 | 0.64 | 0.10 | 0.64 | 0.0 | 0. |
| 11 | 93.750 | 94.833 | 0.000 | 0.90 | 0.00 | 0.00 | 7.1 | 13. |
| 12 | 95.000 | 8.900 | 14.700 | 0.73 | 0.09 | 0.55 | 0.0 | 0. |
| 13 | 239.000 | 3.000 | 12.500 | 0.00 | 7.70 | 2.70 | 7.5 | 0. |
| 14 | 239.000 | . | . | . | . | . | . | . |
| 15 | 239.000 | . | . | . | . | . | . | . |
| 16 | 240.000 | 3.100 | 11.200 | . | . | . | . | . |

```
                              WOOLWICH DOUBLE PACKER TEST
                               ADJACENT PIEZOMETER DATA

                                                                     P
                                         B       T                   M
                                         E       O      C      E     X       O
                  D                      N       L      L      T     Y       X      C    T
     S            E          D           Z       U      B      B     L       Y      U    M    N
 O   I            P          A           E       E      E      E     E       L      M    B    A
 B   T            T          T           N       N      N      N     N       E      E    1    P
 S   E            H          E           E       E      Z      Z     E       N      N    2    T
                                                                             E      E    4    H

 1   4B-4       27.9      10JUN85       4.0    331.9   0.0    79.1   15.5     7.3   0.0   0    0
 2   4B-4       27.9      10JUN85       3.7    381.4   0.0    80.2   16.6     8.5   6.1   0    0
 3   4B-4       27.9      10JUN85       2.8    211.2   0.0    43.7    8.2     3.6  39.2   0    0
 4   4A-6       24.1      21JUN85        .        .     .       .      .       .     .    .    .
 5   4A-7       24.9      21JUN85       4.9   1307.0   0.0   193.6   39.2    19.1   0.0   0    0
 6   4A-7       24.9      21JUN85      20.4   1301.0   4.6   196.5   42.7    23.6   8.8   0    4
 7   4A-7       24.9      21JUN85       0.0      0.0   0.0     0.0    0.0     3.9  20.1   0    0
 8   4A-2       21.0      04JUL85      50.9   4803.0   0.0   818.9  190.0   108.9   0.0   0    0
 9   4A-2B      21.0      04JUL85      66.8   5955.0   0.0   989.6  226.5   129.2   0.0   0    0
```

```
                              WOOLWICH DOUBLE PACKER TEST
                               ADJACENT PIEZOMETER DATA

 OBS SITE  DEPTH  DATE       TOC     CL    CHLORFM TCHLETHA CARTET TCLETHYL PER

  1  4B-4  27.9  10JUN85    12.5   11.1      0       0.0     0.0     0.6     0
  2  4B-4  27.9  10JUN85      .      .       .        .       .       .      .
  3  4B-4  27.9  10JUN85      .      .       .        .       .       .      .
  4  4A-6  24.1  21JUN85   135.0  296.1      0       0.0     0.0     0.6     0
  5  4A-7  24.9  21JUN85   307.8  240.2      0       0.1     0.0     1.1     0
  6  4A-7  24.9  21JUN85      .      .       .        .       .       .      .
  7  4A-7  24.9  21JUN85      .      .       .        .       .       .      .
  8  4A-2  21.0  04JUL85  1035.0  317.0      0       0.2     0.9     1.2     0
  9  4A-2B 21.0  04JUL85  1073.0  325.0      .        .       .       .      .
```

# Appendix D

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## Appendix B

## NORTH BAY LANDFILL SITE

B-1: M.Sc. Thesis - M. Moore (Appendices available from authors on request)

B-2: M.Sc. thesis - K. Ben-Miloud

B-1

# AN INVESTIGATION OF THE PERMEABILITY OF A SAND AQUIFER TO DETERMINE THE CONTAMINANT MASS FLUX OF SELECTED CONTAMINANTS FROM A LANDFILL PLUME

by

MICHAEL BANCROFT MOORE

A thesis
presented to the University of Waterloo
in fulfilment of the
thesis requirement for the degree of
Master of Science
in
Earth Sciences

Waterloo, Ontario, 1986

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# ABSTRACT

An investigation of hydraulic conductivity and leachate migration from a municipal landfill was conducted in an unconfined sandy aquifer near North Bay, Ontario. Chloride samples collected in 1980 and 1985 showed only small changes in plume shape and internal behavior over an extended time period. Plume shape and direction are influenced by a bedrock valley.

Most of the ground water flows through a central stratigraphic zone, which was traced throughout the plume with core samples, water level measurements, and chloride and total organic carbon samples. Hydraulic conductivity is higher, hydraulic head is lower, and chloride and total organic carbon plumes are more concentrated in this central zone than in other zones of the aquifer.

For the central stratigraphic zone, grain-size analyses, permeameter tests, and slug tests provided geometric mean hydraulic conductivity values of 6.0x10-3, 7.0x10-3, and 8.0x10-3 cm/s, respectively. Using the permeameter hydraulic conductivity value in the Darcy equation, an average linear porewater velocity of 175 m/yr was calculated. This velocity, combined with observed chloride and total organic carbon distributions from a total of 760 sampling points in a 0.22 km2 area, provided chloride and total organic carbon mass fluxes of 16 and 14 tonnes/yr, respectively. The total mass of chloride and

total organic carbon within the plume was estimated to be 68 and 59 tonnes, respectively.

The 16 tonnes/yr of chloride discharged from the landfill is much less than one percent of 3,640 tonnes of chloride contained in the road salt used at North Bay each year. The total organic carbon discharge from the landfill of 14 tonnes/yr is equal to less than twelve percent of the 117 tonnes of total organic carbon contained in the treated sewage effluent every year from the City of North Bay. This indicates that the amount of chloride and total organic carbon entering the environment from the landfill is small with respect to other local sources.

# ACKNOWLEDGEMENTS

The author wishes to express his appreciation to a few of the people at the University of Waterloo who offered their time and ideas to this study. Many thanks go to my supervisor, John A. Cherry, for his helpful criticisms and for his inspiration and moral support. Ed Sudicky provided ideas for mathematical interpretation of data and computer graphics. Nancy Gensky helped with the field work. Paul Johnson also assisted in the field program. Sam Vales operated the drilling rig. Mike Zapico and Sam Vales provided the coring device and ideas for its use. Bob Ingleton and Jason Poag assisted with the permeameter experiments. Graham Farquhar contributed his ideas and an important reference. Bob Starr offered his criticisms.

Outside the University, John Miller of the City of North Bay provided historical information on the landfill. The City of North Bay did the surveying. Ray Banach of the Ministry of the Environment (MOE) in North Bay furnished landfill loading rates and population estimates. George Heslope helped with water sampling. Bill Balfour of the MOE in Toronto furnished national deposition rates. Rob Dicken of Gartner Lee Associates provided chloride data from Chippewa Creek. The author wishes to thank the Ontario Ministry of the Environment for the financial support which made this study possible with a grant from

project 118 PL entitled "Hazardous Organic Chemicals in Groundwater at Ontario Landfills".

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# INTRODUCTION

Municipal landfills in non-arid regions produce leachate as a result of infiltration of rain or snow-melt into the refuse. Leachate moves downward through the refuse into the geologic domain. Ground water in this domain normally flows laterally causing contaminant plumes to spread areally from the landfills. Many North American and European landfills are situated on permeable sand or gravel deposits. Leachate plumes in the ground water zone commonly spread laterally from these landfills at rates of about 10 to 1000 m per year. After a few years or decades, these plumes can have adverse effects on wells or surface waters. This paper focuses on the North Bay landfill in northeastern Ontario, a landfill situated on a shallow, unconfined, permeable sand and gravel aquifer. The general features of the contaminant plume at this site have been described by Cherry (1983). The inorganic geochemistry was presented by Buszka (1982), and the distribution and origin of some organic constituents in the plume were determined by Reinhart et al. (1984).

Landfilling at the site, which presently covers 33 hectares, began in 1962 and is continuing at the present. The plume of ground water contamination extends from beneath the landfill to an area of springs 700 m away where springs discharge contaminated water into a forest. The contaminated spring water drains via small channels to a creek that flows through the City of North Bay into a Lake Nipissing.

This investigation determines the velocity and mass flux of selected contaminants in the plume, the total mass of these contaminants in the plume, and the changes in plume shape and internal character that have occurred since monitoring began in 1979. Although many plumes at municipal landfills have been described in the literature, detailed information on rates, fluxes, and temporal character is lacking.

The front of the plume reached the springs in the forest before plume monitoring began seven years ago. Therefore, monitoring the advance of the plume front was not possible as a means of determining the ground water velocity or contaminant mass flux. As an alternative, estimates of representative ground water velocity in the interior of the plume were obtained using the Darcy relation. Values of hydraulic conductivity (K) were determined by slug tests of piezometers, the Hazen relation based on grain-size analyses, and an exceptionally large number of piezometer tests on aquifer core samples.

# SITE DESCRIPTION

The North Bay landfill (Figure 1) is located 7 km from the eastern shore of Lake Nipissing approximately 290 km north of Toronto. Drainage within the study site (Figure 2) consists of a spruce bog on the southern edge of the landfill, a small swamp and pond on its western edge, and intermittent stream drainage to a pond southwest. The southwestern pond is located in the central part of the plume and is fed by leachate springs caused by excavation of a sand pit.

Surface deposit of coarse to fine sands are underlain by a nearly continuous layer of glacial till lying on Precambrian bedrock. The bedrock surface undulates from 5 to 25 m below the ground surface. The sands contain some thin beds of gravel and silt. The bedrock consists of granite, syenite and hornblende-biotite-feldspar gneiss with diorite, diabase, and pegmatite dykes (Harrison, 1972). Its surface is irregular, and generally slopes to the southwest with elevations decreasing from 345 m.a.s.l. below the landfill to 316 m.a.s.l. at the discharge area of Chippewa Creek.

# FIELD AND LABORATORY METHODS

Between 1979 and 1983, Hewetson (1981) and S. Sweeny (written communication) installed 70 multilevel bundles each consisting of nine individual piezometers. In addition, 5 standpipe piezometers, and 25 shallow minipiezometers were placed in the sand and gravel across the study area. There are numerous chloride analyses, water level measurements, and a few geologic logs available from this time period. Fifty of the bundle piezometers were still operational at the beginning of this present study in 1985.

## Piezometer Installation And Use:

The network of piezometers was expanded in May, 1985 by the addition of 34 bundle piezometers and 5 standpipe piezometers in a detailed study area. Four cored holes were also completed in this area as well as two holes outside this area. The detailed study area (Figure 3), about 4000 $m^2$, was established in the center of the leachate plume to observe variations in the hydrostratigraphy, water levels, and leachate concentrations that would probably go unnoticed in a large-scale investigation. Twenty-nine of the bundle piezometers were placed in two lines perpendicular to the general direction of ground water flow. All bundle piezometers were drilled to refusal, which was considered to be the bedrock surface.

The design of the bundle piezometers is essentially the same as described by Cherry et al. (1983). They consist of eight 1.0 cm ID polyethylene tubes bound around a rigid 1.3 cm ID PVC pipe. The ends of each tube were capped, slotted, and wrapped with "Nytex" screen. All of the screened tips on the bundle piezometers in the detailed study area area 30 cm long, and spaced 60 cm apart. The construction method and other details pertaining to the bundle and standpipe piezometers are included in Appendix A. The construction of piezometers installed before 1985 are similar to those described above (Hewetson, 1981).

The 5 standpipe piezometers were installed in the detailed study area (Figure 3) in May 1985 using hollow-stem augers. They consisted of 240 mesh "Timco" PVC screens, 3.05 meters long with an OD of 6.0 cm, glued to 6.0 cm OD PVC pipes. These piezometers were placed at the same depth and equally spaced horizontally. The screens were installed from 5.9 to 9.0 meters below ground surface.

Water level measurements in most bundle piezometers were recorded monthly from May to October 1985 with an electric contact probe. Results were reproducible within ± 5.0 mm.

A battery-driven perisaltic pump was used to collect groundwater samples for chloride and total organic carbon through 5 mm OD "Teflon" tubing into 20 milliliter glass bottles with "Teflon" disk caps. Samples of total organic carbon were preserved with phosphoric acid ($H_3PO_4$) and refrigerated immediately. After sampling at each bundle, the "Teflon" tubing was thoroughly rinsed inside and out with a 10% HCl solution followed by distilled water.

Aquifer Coring:

Sediment core samples were collected in aluminum tubes using a 1.5 m long piston sampler and hollow-stem augers. Six locations in line with ground water flow from the landfill were cored, as shown on Figure 3. One borehole was beside bundle G near the edge of the landfill (Figure 3). Four boreholes were spaced 20 m apart in an approximate line from bundles MM9 to API about 180 m from the landfill (Figure 3). A sixth borehole was cored near bundle LL 360 m from the southwestern corner of the landfill.

The coring device, described in detail by Zapico et al. (1986), consisted of a removable aluminum tube 1.52 m long with an ID of 4.7 cm encased in a protective steel tube with a hardened steel cutting head. The sampler was attached to the center rod, lowered through the hollow-stem auger, and driven by a hydraulic hammer five feet into geologic material. The sampler was then detached from the center rod while at the bottom of the hole and lifted by a cable to the surface. During the time it took to auger the next 1.5 m, the aluminum tube containing the sediment was removed. A new tube was placed in the steel housing and the next sample was taken.

### Measurements of Hydraulic Conductivity:

Permeameter tests were performed on 759 subsamples of the core materials. The aluminum core tubes were split along the core axis, the material from one of the half cores was subdivided into 5 cm subsamples and oven dried. The 5 cm sample length was short enough to generally represent sediment from only one depositional unit. Fifty grams of each subsample were packed into a permeameter. After passing $CO^2$ upward through the sample in the permeameter, the sample was saturated with de-aired water under upward flow conditions. The K value was determined by standard falling-head methods. All results are listed in Appendix B.

To obtain K values using the Hazen method (Freeze and Cherry, 1979, p.350), grain-size analyses were conducted on selected samples from the core halves not used for permeameter tests. Samples were selected from cores to represent all textural types present. A total of 67 tests of 43 samples were accomplished using ASTM standard methods (U.S. Bureau of Reclamation, 1974) with the mechanical method used for coarse-grained sediment and the hydrometer method for fined-grained material. Both the mechanical and hydrometer methods were used on samples containing enough fine material to justify both tests. Between 50 and 100 grams of material were used in each test. Results and grain-size curves are presented in Appendix C.

From June to August, a total of 16 falling-head and 5 rising-head slug tests were conducted using a solid aluminum slug, 2 cm in diameter and 1.46 m in length, on the five Timco-screen piezometers. The changes in water level with time were measured with an electric contact probe and a stopwatch.

# RESULTS AND DISCUSSION

## Hydrostratigraphy:

Detailed descriptive logs and profiles of hydraulic conductivity (K) with depth were obtained for each of the six coreholes, GB, LLB, and MB1 through MB4 (Figure 3, Appendix B). Coring at the North Bay site involved experimentation with the newly-developed coring device; therefore, the recovery for some cores was not complete.

Three major stratigraphic zones above the bedrock were identified (Figure 4). The bedrock surface is overlain by about a meter of poorly-sorted glacial till. The till is an unstratified mixture of mostly silt and fine sand with less than 5% clay, and various sizes of gravel up to the 4.7 cm core barrel ID. It is covered by about 3 to 20 m of interbedded coarse, medium, and fine sand. This zone is mainly massive, well sorted, fine-grained sand. The four boreholes in the detailed study area, MB1 through MB4, show this zone to be covered by a meter or more of massive, fine sand and silt only found in this area. Evidence of a low energy depositional environment came from the lack of obvious cross bedding in the cores, and the predominance of massive, well sorted, fine sand. Some bedding contacts were sharp with individual beds a few centimeters thick, but most contacts were gradational with bed thicknesses of tens of centimeters. Hewetson (1981) concluded that some zones in this aquifer were deposited in a glaciolacustrine environment and other zones in a glaciofluvial environment. The core samples described above indicate the predominance of a glaciolacustrine environment.

The upper layer of fine sands and silts found in coreholes MB1 through MB4 is referred to as the "A zone", the central zone of medium and fine sand found in all coreholes is the "B zone", and the bottom layer of silts and till encountered in all coreholes except MB4 is the "C zone". These zones are apparent in the K and hydraulic head profiles of Figure 5, which shows the B zone to have higher K and lower hydraulic head values than the other two zones. The K values presented in Figure 5 represent the geometric mean of each zone from all permeameter tests from the six coreholes.

Vertical hydraulic gradients exist in the aquifer. At some monitoring sites the hydraulic-head profiles show the effect of the stratigraphy as seen in Figure 5 and Appendix B. Each plotted line represents a different month with a drop in the water level of about one meter from June to October. A full hydraulic head profile that includes all three zones was not obtained from most sites because these wells were not drilled into the till zone, piezometers were placed below the A zone, or the A zone was not present.

## Plume Delineation:

Chloride (Cl) was used to indicate the general degree of contamination at the North Bay site. This parameter was used because it is non-reactive in the aquifer, has a high concentration in the leachate, and has very low background concentrations in the aquifer. Total organic carbon (TOC) is used as a secondary indicator of the degree of contamination.

A comparison of Cl data from Hewetson's (1981) study to that collected in 1985 (Figure 6) showed only small changes in the plume shape. There has been a change in the extent of the zone of high contamination. The front of the 200 and 300 mg/L contours has moved down gradient approximately 330 and 170 m, respectively. The positions of contours of 100 mg/L or less and 400 mg/L or greater have remained relatively unchanged. Internally, the 1985 plume follows nearly the same path as the 1980 plume (Figure 7). Exact comparisons of the 1980 and 1985 plumes are not possible because the locations of many monitoring points changed in this period as some piezometers were destroyed and others were installed at different positions.

The distribution of TOC is contoured in plan in Figure 8, and Cl and TOC in cross sections parallel and perpendicular to ground water flow in Figures 7, 8, and 9. Cross section lines are shown in Figure 3. All contours in plan are based only on the highest concentration detected in each bundle piezometer. Maps of the Cl and TOC data for other months are presented in Appendix D.

The lowest concentrations of Cl and TOC were consistently measured in bundles 00 and X, which gave maximum values of 0.5 and 1.1 mg/L, respectively. These piezometers are situated outside the plume. Water with concentrations greater than these values was considered to be contaminated from landfill leachate. Contour lines as low as 5 mg/L were drawn only where there were a sufficient number of piezometers to provide reasonable control.

The width of the plume interior is discussed in terms of the 200 mg/L contour line because it is one of the lowest concentrations which can be thoroughly traced using the existing network. In Figure 6 August 1985, the 200 mg/L contour line shows that the Cl plume reaches its greatest width of 215 m about 100 m from the southwestern corner of the landfill. The plume reaches its narrowest width of about 35 m approximately 170 m further to the southwest.

A comparison of the 200 mg/L contour line with the bedrock contour map (Figure 2) illustrates the influence of the bedrock topography on the shape of the plume. The bedrock contour map reveals a bedrock valley floor dipping to the southwest with a well defined southern slope and a probable northern slope. The plumes of Cl and TOC in Figures 6, 7, 8, and 9 follow two trends. The contour shape conforms to the bedrock valley, and the highest concentrations can be found within the stratigraphic zone B. Cross section D-D' (Figure 3 and 9) shows a better perspective to observe the effect that the bedrock valley has on confining the highest concentrations of Cl and TOC in the plume.

The highest Cl concentrations in the aquifer were encountered at the southwestern tip of the landfill, where they varied from 335 mg/L in May to 661 mg/L in October. The highest Cl concentrations measured in piezometers farthest from the landfill at the springs varied from 69 mg/L in May to 95 mg/L in October. Therefore, on a percentage basis the maximum observed variability of Cl was not substantially reduced along the 700 m long travel path.

Overall, the shape of TOC contours resemble the Cl contours in cross section and in plan (Figures 6-9 and Appendix D). Ratios of Cl/TOC in bundle piezometers from the landfill to the springs were compared and there appears to be no consistent increase or decrease with distance. This implys that there may be no retardation of the measured bulk organic carbon or Cl with distance.

Hydraulic Conductivity:

The K tests were performed at an average room temperature of 20° C. Because the average ground water temperature in the aqufer is close to 8° C, a temperature correction based on viscosity and density was necessary to represent the field K. The laboratory values were divided by 1.39 to obtain the field values. All permeameter values reported here are the values corrected to field temperature.

Many permeameter tests were repeated to assess the variability in K values for test repetition on a remixed subsample and for various sample compaction efforts. If permeameter K values are not substantially effected by remixing or compaction then there is allowable error in achieving field bulk densities and porosities for representative field K values. The sample textures ranged from coarse sands with K values of 5x10-2 cm/s to sandy silts with values of 5x10-5 cm/s. The difference in K values obtained from 60 repeated remixed samples as compared to initial K values was small, less than one sixth an order of magnitude. A second repetition using a range of compaction efforts on the same 60 samples showed a difference of less than half an order of magnitude in K values. Compaction was accomplished by vibrating the samples using various vibrating instruments. Seventy-five percent of the repeated tests provided K values less than one third an order of magnitude from the initial test values regardless of the method of compaction or the degree of compaction. The K values for repeated compaction tests on coarse and medium sands were closer to the original values than fine sands and silts.

The K profiles for coreholes MB1 through MB4 (Appendix B) show a trend of relatively low K in the A zone. All coreholes show a higher K in the B zone, and much lower K in the C zone, except MB4 in which the C zone is missing. Examples of two detailed K profiles along with the geometric mean K value for each zone based on all cores are shown in Figure 5. Statistical information is presented in Table 1. Geometric means are presented because log-transformed K values more closely resemble a Gaussian distribution than non-transformed K values.

From the weights and volumes of dry samples packed in the permeameters, values of porosity were obtained ranging from 0.33 to 0.51 with a mean of 0.43. These porosity values pertain to the samples in a re-packed state and not to the relatively undisturbed samples as they occur in the cores.

Twenty-one slug tests were conducted on the five Timco-screen piezometers, all of which are located in the B zone in the detailed study area. From the rising and falling-head tests, an overall geometric mean K value of 8.18x10-3 cm/s was ascertained. Results for the slug tests are presented in Appendix C. The coreholes situated closest to these Timco-screen piezometers are MB1 and MB2. The geometric mean for 140 permeameter test values from zone B in those coreholes is 3.31x10-3 cm/s.

Grain-size analyses were conducted on 43 samples of different textures from the three stratigraphic zones. The grain-size graphs are displayed in Appendix C. These analyses were used to obtain K values with the Hazen relation,

$$K = Cd_{10}^{2}$$

where
$K$ = hydraulic conductivity (cm/s)
$C$ = empirical constant
$d_{10}$ = grain size diameter (mm) at which 10% by weight of the soil particals are finer and 90% are coarser.

The constant C varies from 0.4 to 1.2 with an average value of 1 (Holtz and Kovacs, 1981), which is the value used for all calculations in this study. The relation was originally developed by Hazen (1911) based on many tests of clean sands (less than 5% passing the No. 200 sieve), but it is now normally applied to sediment having a much wider range of grain sizes. The equation is best suited for sand that has $K \geq 10-3$ cm/s (Holtz and Kovacs, 1981). The Hazen equation is used here in preference to other empirical relations for determining K from grain-size data because it is most widely used in the field of hydrogeology.

Six samples were chosen from each of seven catagories selected on the basis of permeameter results. Each category represents samples within a K range of half an order of magnitude, from 5.0x10-2 cm/s to 5.0x10-5 cm/s. The geometric means (temperature corrected to 8° C) of K values from the Hazen relation for zones A, B, and C are 5.45x10-4, 5.96x10-3, and 1.23x10-4cm/s, respectively. The mean value for the A, for which there were only five samples, zone differs by about half an order of magnitude from the geometric mean obtained for the A zone from permeameter tests (Table 1), and the B and C zone differ by less than one ninth an order of magnitude. Figure 10 shows the close correlation in K values for the two methods. Out of 43 samples, 27 had lower values than the permeameter tests and 16 had higher values. Because the mean value of K for each of the stratigraphic zones has not been determined accurately by a third independent method used intensively, there is no basis for judging if the Hazen results are more or less representative than the permeameter results. The close agreement between the Hazen method and the permeameter values indicate that permeameter tests and grain-size analyses serve equally well for determination of K values. The permeameter method is the preferable method because analysis is three times faster and costs are much lower. One technician is able to do at least three times the number of permeameter tests than grain-size analyses in the same time period.

Ground Water Velocity And Contaminant Fluxes:

The Darcy equation,

$$\bar{v} = -\frac{Ki}{n},$$

where
$\bar{v}$ = average linear porewater velocity (cm/s)
i = slope of the water table
n = porosity of the aquifer
K = hydraulic conductivity (cm/s)

was used to estimate the average linear velocity of ground water flowing laterally in zone B from the landfill to the springs (bundle G to TT, Figure 3). The horizontal gradient used for this equation was based on water level measurements taken from May to October 1985. Figure 11 is a typical water-table map showing flow toward the southwest, with a discharge zone at the springs near Chippewa Creek. The average horizontal gradient from bundle DD to L is 0.035, from L to U is 0.010, and from U to TT in the discharge zone is 0.044. The horizontal component of the hydraulic gradient across the plume area between bundles DD at the edge of the landfill and TT at the springs is 0.034.

The Cl and TOC distributions (Figures 7-9) indicate that the leachate flows primarily through the B zone. The profiles of K and the distributions of hydraulic head across the overburden show that this is the most permeable zone. Using the geometric mean K value obtained from permeameter tests of 7.0x10-3 cm/s for the B zone, a porosity of 0.4, and the horizontal hydraulic gradients mentioned above, a $\bar{v}$ can be calculated for three lateral segments of the B zone. The $\bar{v}$ from bundle DD to L (a distance of 360 m) is 180 m/yr, from L to U (a distance of 225 m) is 50 m/yr, and from U to TT (a distance of 465 m) is 225 m/yr. The $\bar{v}$ becomes 175 m/yr if the average gradient from DD to TT of 0.034 is applied. Taking 175 m/yr as a representative velocity, a non-reactive contaminant can travel from the landfill to the springs in about 4 years. There is some uncertainty associated with this travel-time estimate, primarily due to the uncertainty in the K value used in the calculations. It is expected that this uncertainty is small because the geometric means from the Hazen and slug tests values for the B zone (Table 1) are very close to the mean from the permeameter tests. The $\bar{v}$ from DD to TT for the B zone using geometric means from the Hazen and slug tests are 150 and 200 m/yr, respectively. The uncertainty in the velocity attributable to the porosity is small. The mean value for the porosity of the B zone, although it has not been measured directly, is undoubtedly in the range of 0.33 to 0.45. For a less well sorted sand in Ontario, carefully measured values of porosity had a mean of 0.34 (Sudicky, 1986). The sand in the B zone is better sorted; therefore, the porosity is expected to be close to 0.4. Although the water levels vary considerably seasonally, the uncertainty in the gradient is small because the lateral gradient remains nearly constant.

The mass flux of Cl and TOC was obtained by multiplying the Darcy flux by the area and by the average concentration from cross section B-B' (Figure 3 and 9). Cross section B-B' was contoured as low as 5 mg/L and divided into 269 squares. The average Cl concentration was obtained by averaging the Cl concentration at each corner of a square from the contour lines. The average Cl concentration for each square was multiplied by its area and the Darcy flux, and the sum of the 269 squares provided the mass flux. A mass flux of 16 tonnes/yr of Cl and 14 tonnes/yr of TOC was obtained. The travel time from cross section B-B' to D-D' is about three years; therefore a mass flux through D-D' (Figure 3) calculated in 1985 represents leachate from 1982. Estimates of Cl and TOC mass flux through cross section D-D' provide results of 12 and 13 tonnes/yr, respectively. Because there were more bundle piezometers sampled from cross section B-B' than D-D', B-B' provided for more detailed contouring of the Cl concentration; therefore, the mass flux from B-B' is likely more accurate and is used in the discussion below.

## Contaminant Masses In The Plume:

The total mass of Cl and TOC in the plume was obtained by multiplying the average concentration by the area, by the depth, and by the average porosity. To obtain the average concentration for a total mass calculation, vertical lines were drawn through cross sections from the water table to bedrock. Each line was divided into about 12 equal length segments. The concentration was averaged along these lines per unit depth using the contour lines, and an average concentration recorded from these vertical lines on a plan view map. Numerous vertical lines drawn on four cross sections provided many average concentration values recorded on a plan map. A large number of average concentration values generated a detailed contour map. This contour map was again divided into many squares with the average concentration calculated for each square as above in the mass flux calculation. The average concentration for each square was multiplied by its volume and the average porosity of 0.43. The results provided a total mass of 68 tonnes of Cl and 59 tonnes of TOC. The same calculations using Hewetson's data from August, 1980 provides a total mass of 48 tonnes of Cl in the leachate plume (1980 samples were not analyzed for TOC). Fewer piezometers were sampled in 1980; therefore, the total mass calculation for 1980 is probably not as accurate as the 1985 result.

Loading and Leaching:

The North Bay landfill opened in 1962 as an abandoned sand pit to receive all refuse from the City of North Bay and from the former Township of West Ferris. Since then it has received domestic, commercial, solid industrial, and some liquid industrial wastes. According to the Ontario Ministry of the Environment (Ray Banach, personal communication), the average rate of deposition of refuse in the North Bay landfill is about 100 tonnes/day. From 1962 to 1975 the population increased from about 39,000 to 50,000, and to 53,000 by 1985. The annual loading, which was mostly domestic waste, to the landfill was 36,500 tonnes in 1985. This represents a daily deposition rate of 2.0 kg per capita. This is close to the average per capita production of municipal refuse in Canada, which is estimated to be 2.5 kg/day in urbanized areas (Bill Balfour, Ontario Ministry of the Environment, personal communication).

In a laboratory investigation of leachate production from sanitary landfills, Fungaroli and Steiner (1979) performed a lysimeter experiment in which they leached approximately 2,000 kg of fabricated municipal refuse in a large lysimeter for about four and a half years. After four and a half years of continuous leaching with 421.5 gallons of distilled water per year, which is equal to 47.7 cm of infiltration per year, they found that about 90% of the available chloride had been removed from the refuse. The refuse composition was patterned after the analysis of Kaiser (1966), who presented data for typical municipal waste. The refuse contained 2.0 mg of Cl for every gram of refuse, which was based on samples of the refuse before emplacement in the lysimeter. If it is assumed that each gram of North Bay waste contains 2.0 mg of Cl, then the 36,500 tonnes of waste deposited in 1985 would contain close to 73 tonnes of Cl. Environment Canada reports an annual precipitation of 96.4 cm in the North Bay area. Based on results from a study completed on a similar soil in an area of Ontario 225 km south of North Bay, Egboka et al. (1983) states that 50% of the precipitation is infiltration. Fifty percent of the annual precipitation in the North Bay area would equal 48.2 cm/yr of infiltration, which is very close to the 47.7 cm/yr used by Fungaroli and Steiner (1979). Because of the similar infiltration rates, there is a basis for comparing the leaching rate of the lysimeter experiment to that of North Bay.

Knowing the population of the area served by the North Bay landfill since 1962 and assuming an average deposition rate of 2.0 kg per capita per day since 1962, it is possible to obtain the amount of Cl deposited in the landfill each year if there is 2.0 mg of Cl per gram of refuse. At the Fungaroli and Steiner (1979) leaching rate of 90% every four and a half years, the North Bay landfill would contain 218 tonnes of Cl by the end of 1985. If landfill deposition stopped in 1985, this 218 tonnes of Cl would leach out of the landfill by the end of 1990 at an average mass flux rate of 44 tonnes/yr.

The measured mass flux rate through cross section B-B' in 1985 was 16 tonnes/yr. The measured mass flux rate through cross section D-D' was 12 tonnes/yr, which represents landfill leachate from 1982 because the travel time from B-B' to D-D' is three years. Continuing this decreasing mass flux rate of 4 tonnes every 3 years, there would be no mass flux of Cl through B-B' by 1973 and a net total accumulation of about 1,550 tonnes of Cl in the landfill by the end of 1985. If landfill deposition stopped today and the current leaching rate of 16 tonnes/yr were to continue, it would take about 97 years for all of the Cl to leach out of the landfill. The basis for assuming a lower mass flux rate in the past is from a measured Cl mass flux rate through D-D' of 12 tonnes/yr which represents landfill leachate from 1982, and the measured total amount of Cl in the plume in 1980 from Hewetson's data of 48 tonnes as compared to the 68 tonnes in 1985. In comparison, the lysimeter leaching rate from Fungaroli and Steiner (1979) does not match what was measured in the field. It is possible that the 2.0 mg of Cl per gram of refuse is an incorrect assumption for the North Bay refuse. It must also be considered that the measured mass flux rate of 16 tonnes/yr of Cl through B-B' is a maximum rate.

## IMPLICATIONS:

In the vicinity of the landfill, Chippewa Creek is small with a typical width between 1.2 and 2 m, a channel depth of 10 to 20 cm, and a flow rate that varies between about 0.9 and 6 $m^3$/min. The concentration of Cl in the creek just downstream from the discharge springs, measured by Gartner Lee Associates from May 1985 to March 1986, had an average Cl concentration of 43 mg/L (Rob Dicken, personal communication). Therefore, the Cl contribution from the landfill to the surface water is relatively large because the streamflow is small.

The City of North Bay reported purchasing an average of 6,000 tonnes/yr of road salt in 1985, which is equal to 3,640 tonnes of Cl/yr. The mass flux of Cl from the North Bay landfill is 16 tonnes/yr, which is much less than 1% of the annual Cl loading from road salt. Both the Cl from the road salt and the landfill end up in Lake Nipissing. The results of this study indicate that the loading of landfill Cl to the lake is insignificant relative to the road salt Cl.

Wilson (1975) found an average of 12 to 15 mg/L of TOC in treated sewage effluent from an urbanized area of southern Ontario. The average volume of treated effluent discharge by North Bay into Lake Nipissing is $3.0x10^7$ L/day. If it assumed that this effluent contains 12 mg/L of TOC, then about 117 tonnes of TOC per year is drained into Lake Nipissing. The landfill loading of 14 tonnes/yr of TOC into Chippewa Creek is small relative to treated sewage effluent TOC.

# SUMMARY OF CONCLUSIONS

The plume occurs in three major stratigraphic zones. Ground water flow occurs primarily in the middle stratigraphic zone consisting of coarse to fine sand.

Since 1980 when monitoring began, the change in plume shape has been minimal. The 200 and 300 mg/L Cl contour fronts have shifted downgradient 330 and 170 meters, respectively. Contours of 100 mg/L or less and 400 mg/L or more have not changed. The core of the plume still follows a central path through the B stratigraphic zone.

Mean K values obtained from grain-size analyses and permeameter tests are similar, but the permeameter tests cost much less. The geometric mean of many permeameter tests provided a K value representative of the field K of 7.0x10-3 cm/s for the middle stratigraphic zone. This geometric mean K value combined with an average horizontal gradient of 0.034 produced an average linear porewater velocity of 175 m/yr. Therefore, a nonreactive contaminant can travel from the landfill to the springs 700 meters away in about 4 years.

A Darcy flux and many Cl and TOC samples made it possible to calculate a mass flux of Cl and TOC through the plume of 16 and 14 tonnes/yr, respectively. By combining a bedrock topography and water table map, a plume volume was acquired. After multiplying the plume volume by the average concentration and porosity, a total mass of 68 tonnes of Cl and 59 tonnes of TOC was obtained. Using the results from a lysimeter experiment by Fungaroli and Steiner (1979), it was possible to calculate a deposition rate of Cl at the North Bay landfill of 73 tonnes in 1985. With a Cl leaching rate of 90% every four and a half years from Fungaroli and Steiner (1979), all Cl would be leached from the landfill by 1990. At the measured field leaching rate, all Cl would be leached from the landfill by 2082.

The amount of Cl released from the landfill is much less than one percent of the Cl applied yearly to roads in North Bay and is equivalent to 6 average-size dump trucks filled with salt. Both the landfill and the road salt Cl end up in Lake Nipissing.

The mass flux of 14 tonnes/yr of TOC from the landfill is equal to about 12% of the TOC discharge from the North Bay sewage treatment plant to Lake Nipissing.

When gross indicators of contamination are considered, such as Cl and TOC, this landfill and probably many others are relatively small contributors to overall surface water loading in humid regions where large lakes or rivers exists. This does not imply that landfills pose no threat to the environment, but that concern over landfills should probably be focused more towards toxic substances such as organics.

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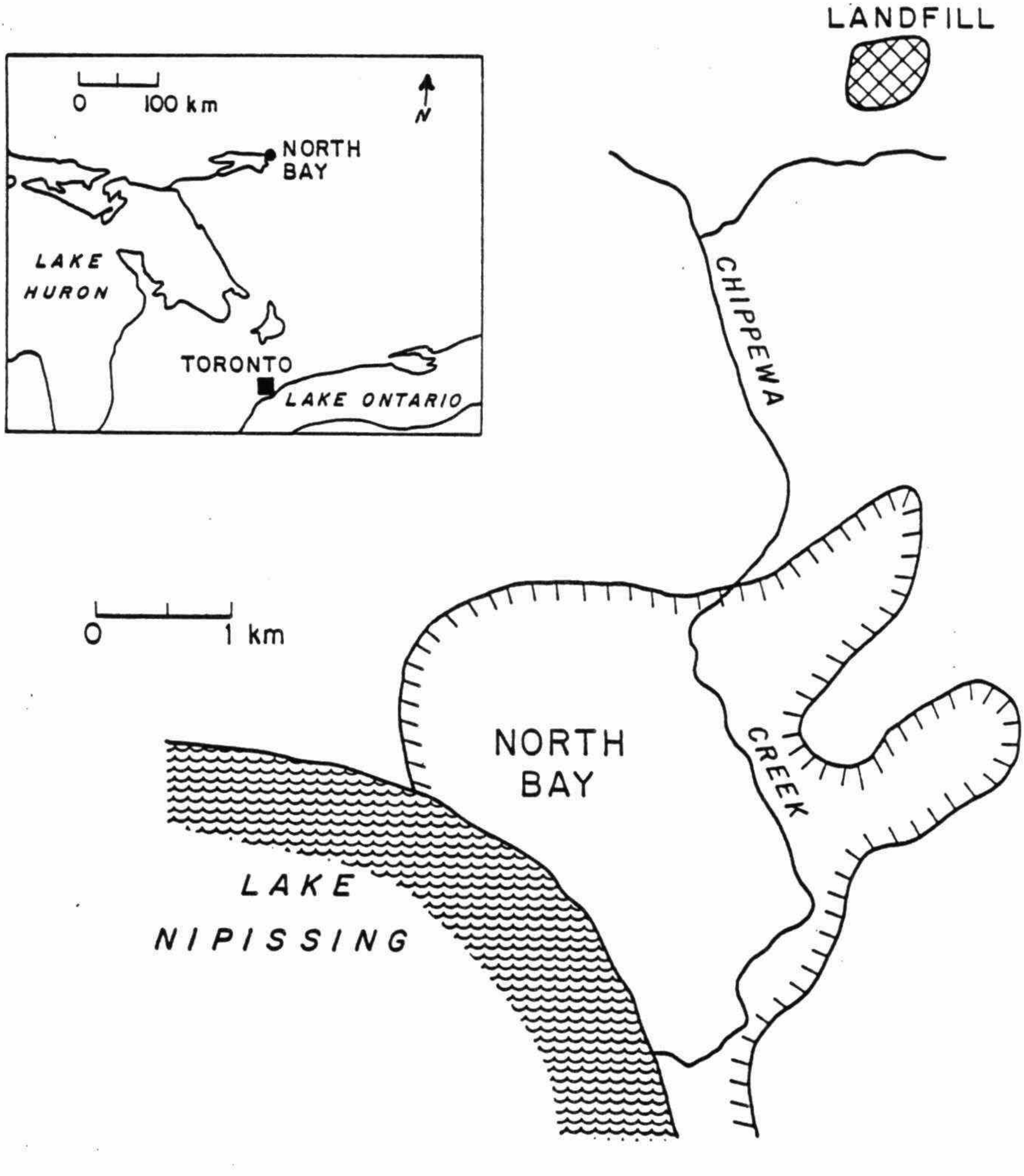

Figure 1. Site Location Map.

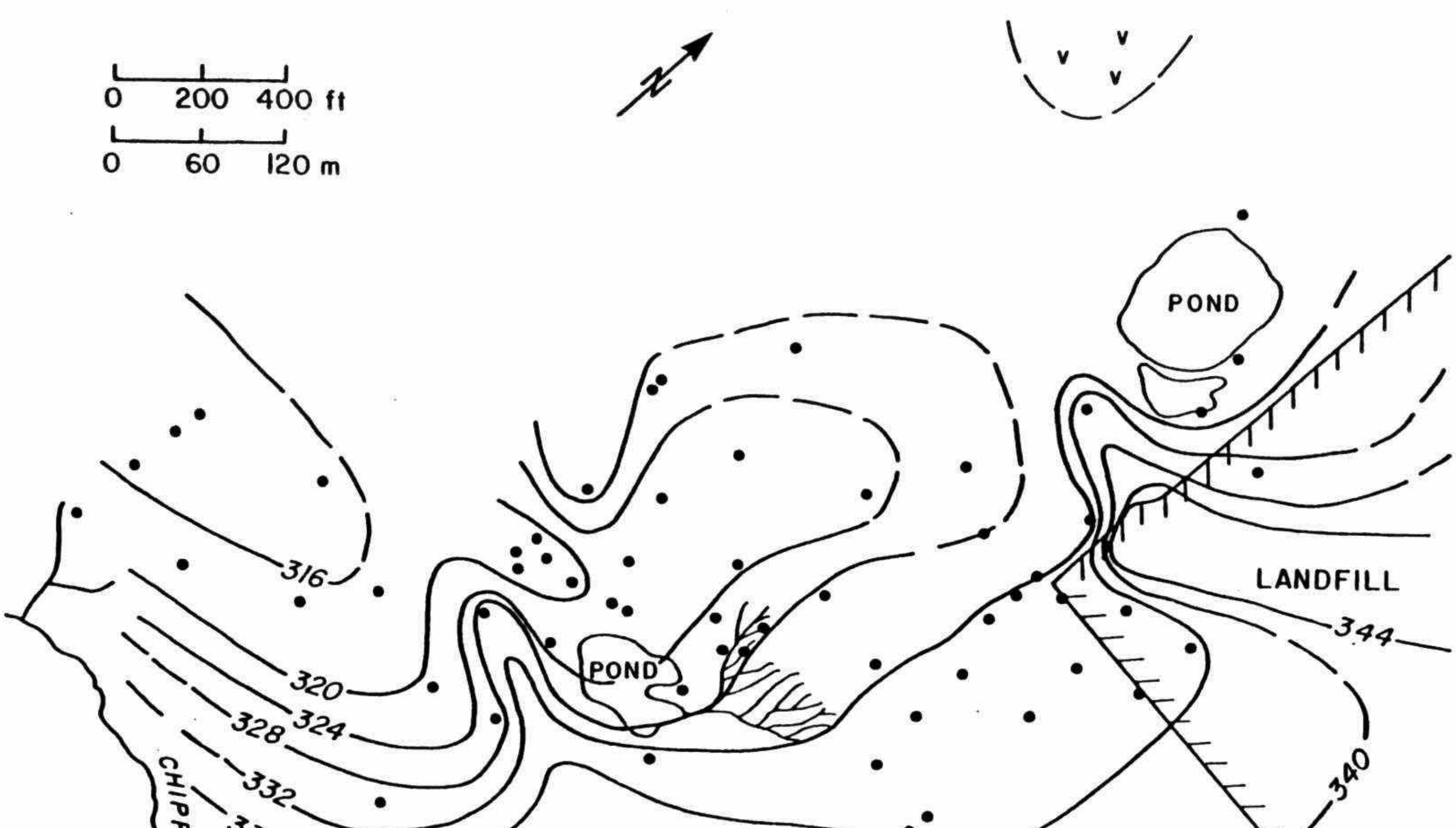

Figure 2. Bedrock Topography (m.a.s.l.).

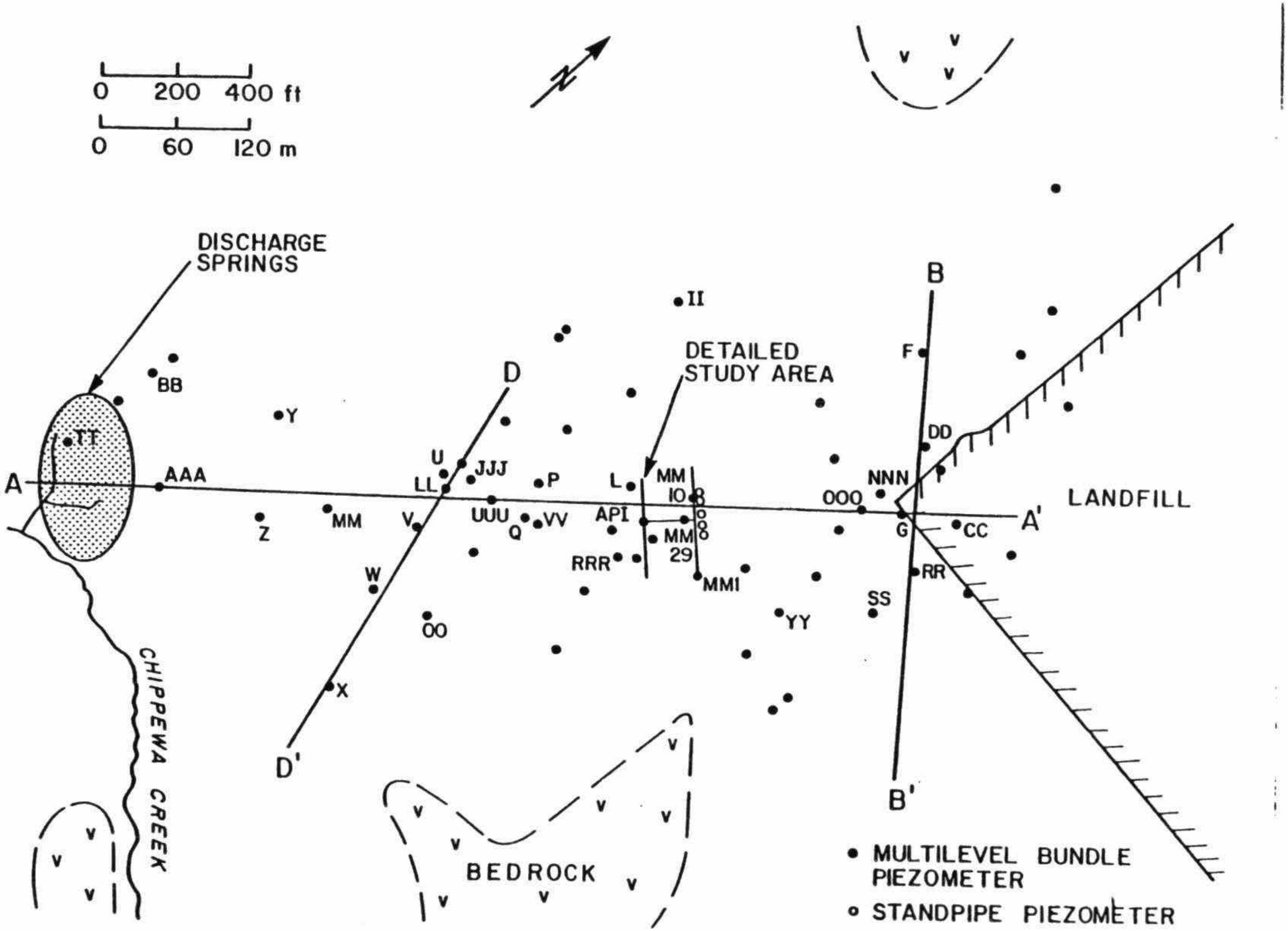

Figure 3. Cross Sections And Bundle Piezometer Locations.

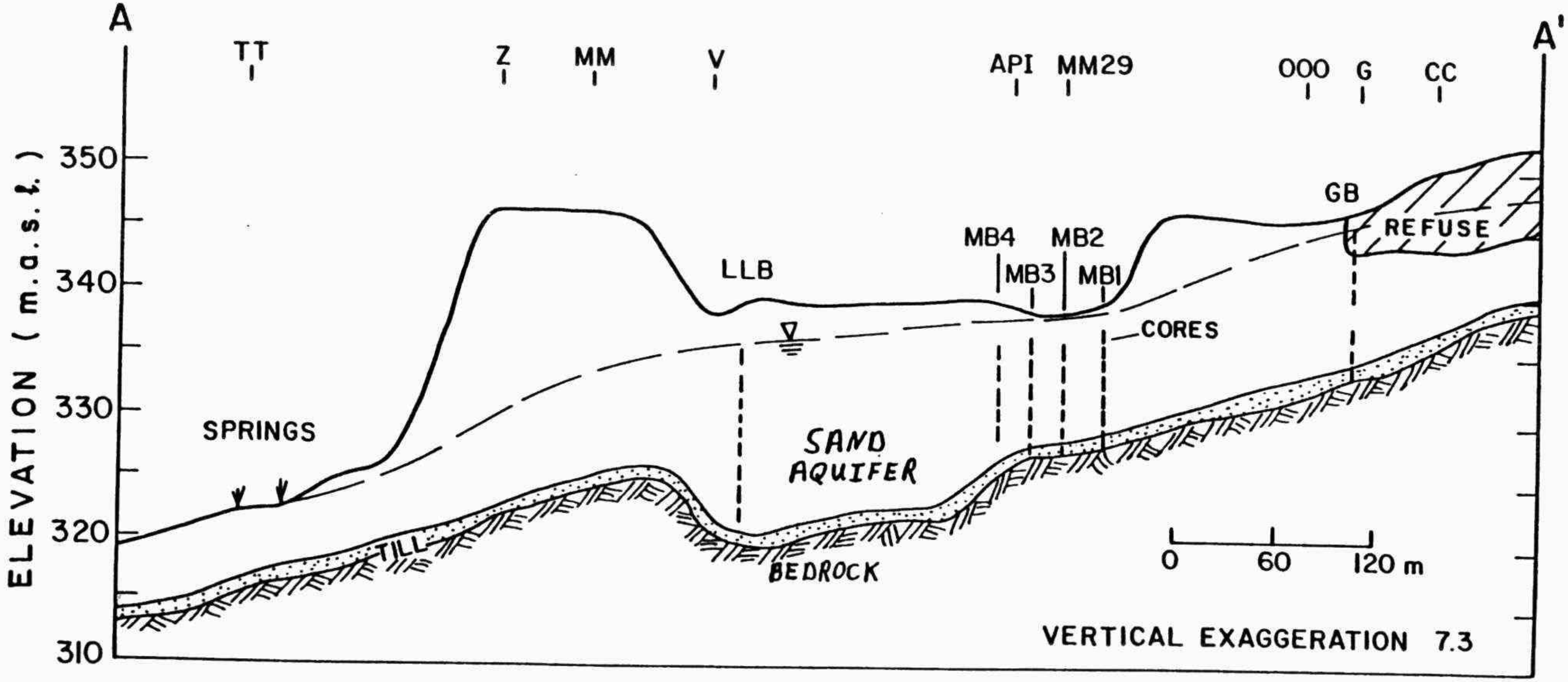

Figure 4. Stratigraphic Cross Section A-A'.

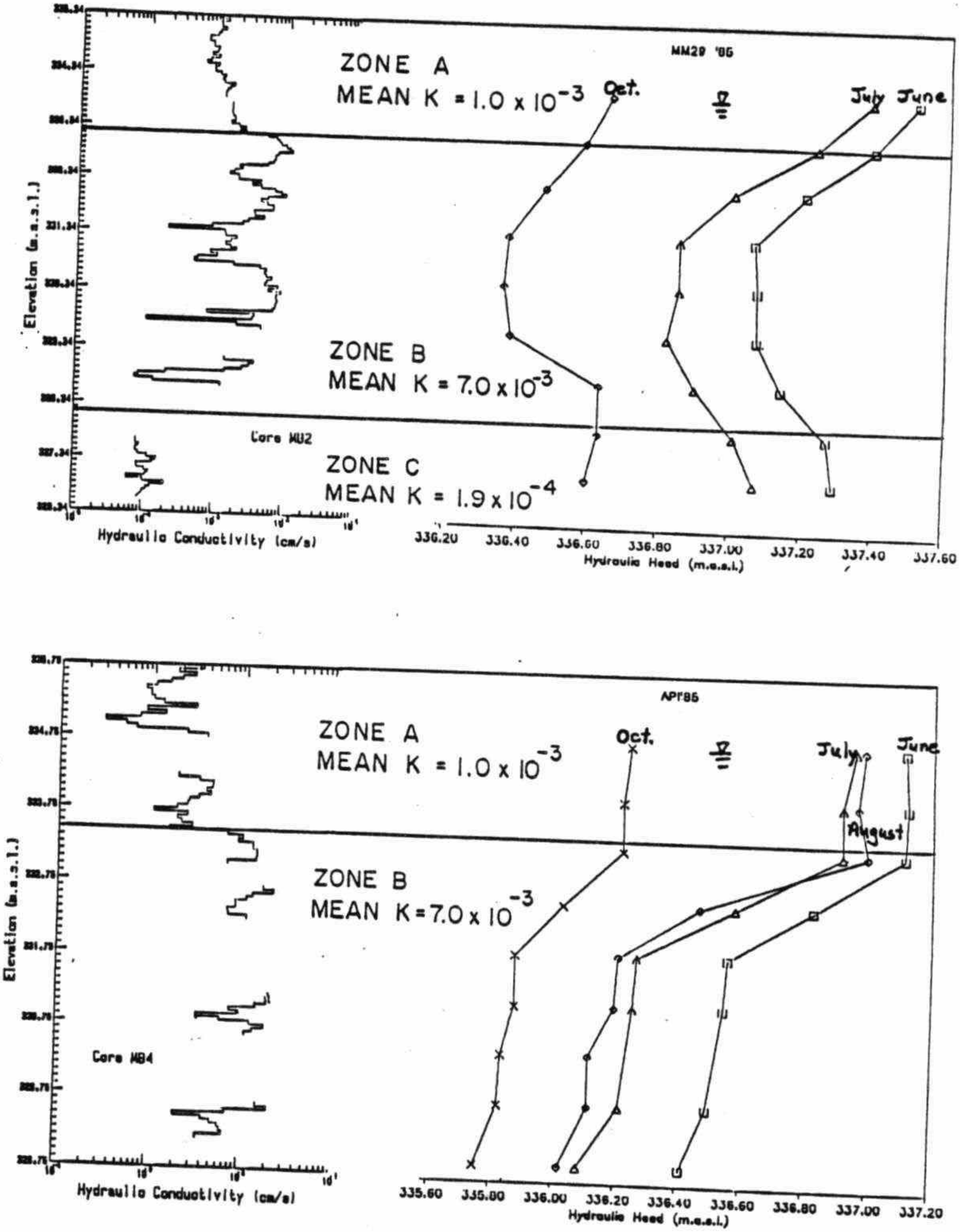

Figure 5. Hydraulic Conductivity And Hydraulic Head Profiles.

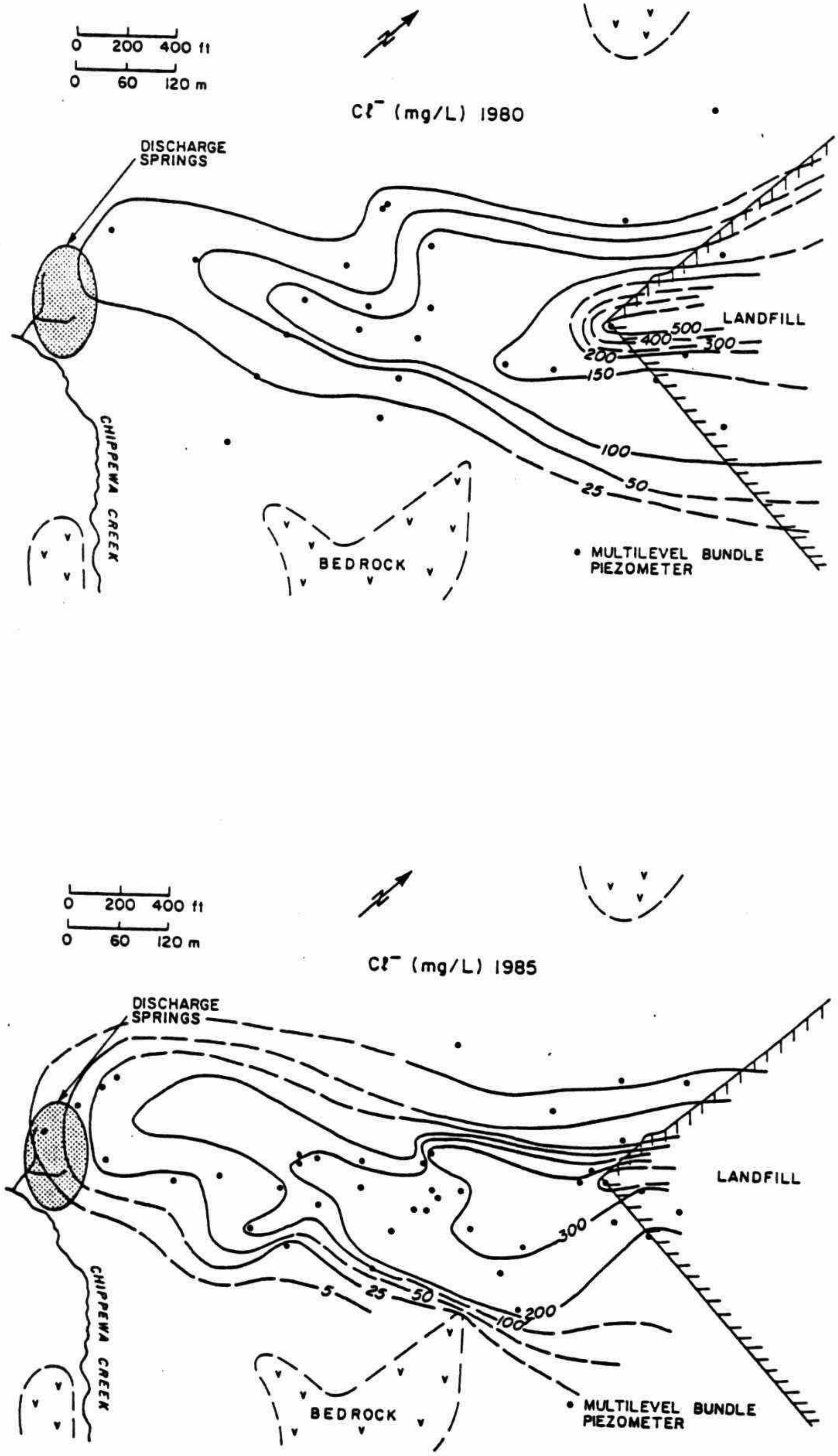

Figure 6. Chloride, August 1980 And 1985.

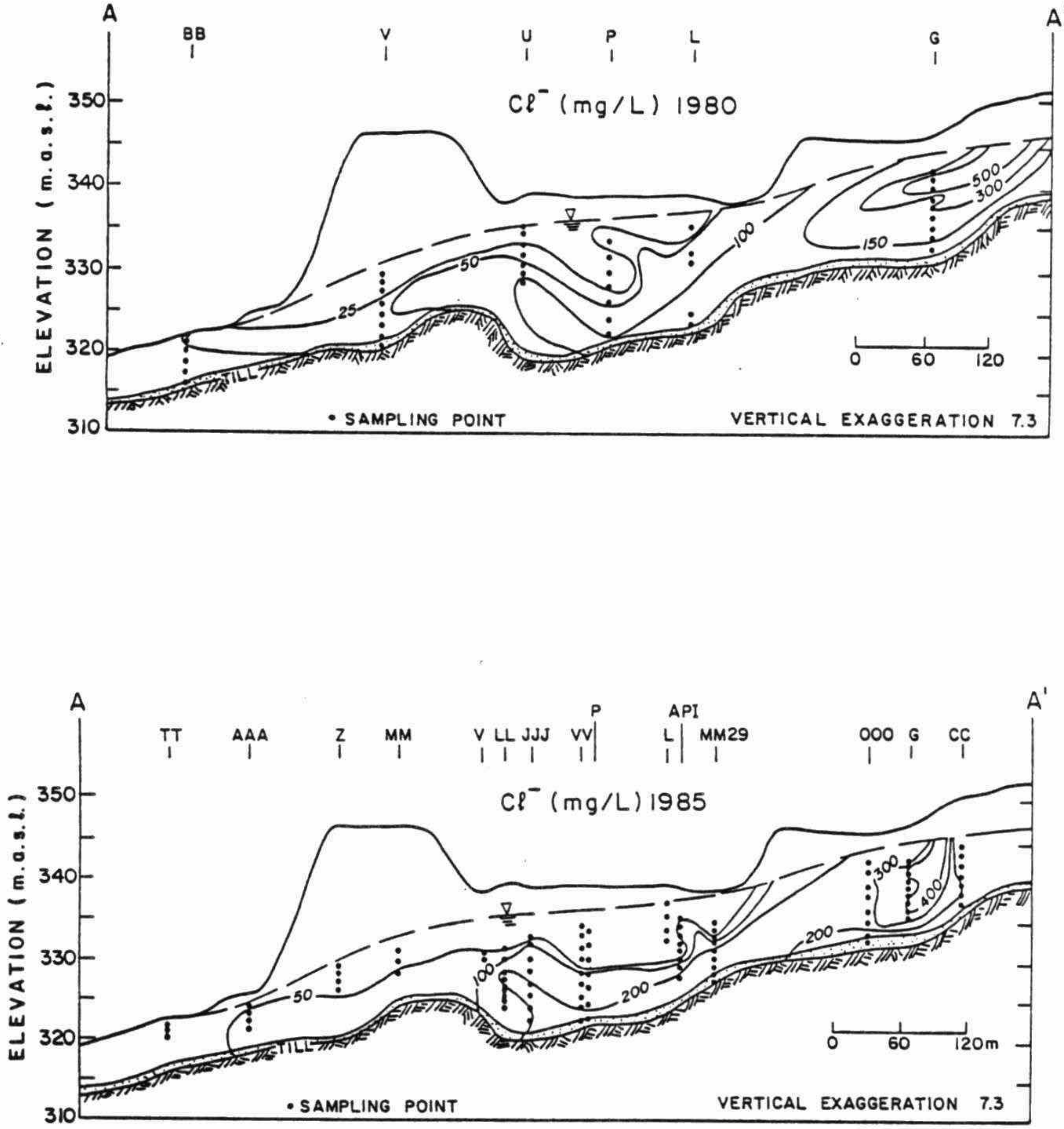

Figure 7. Chloride Cross Sections, August 1980 And 1985

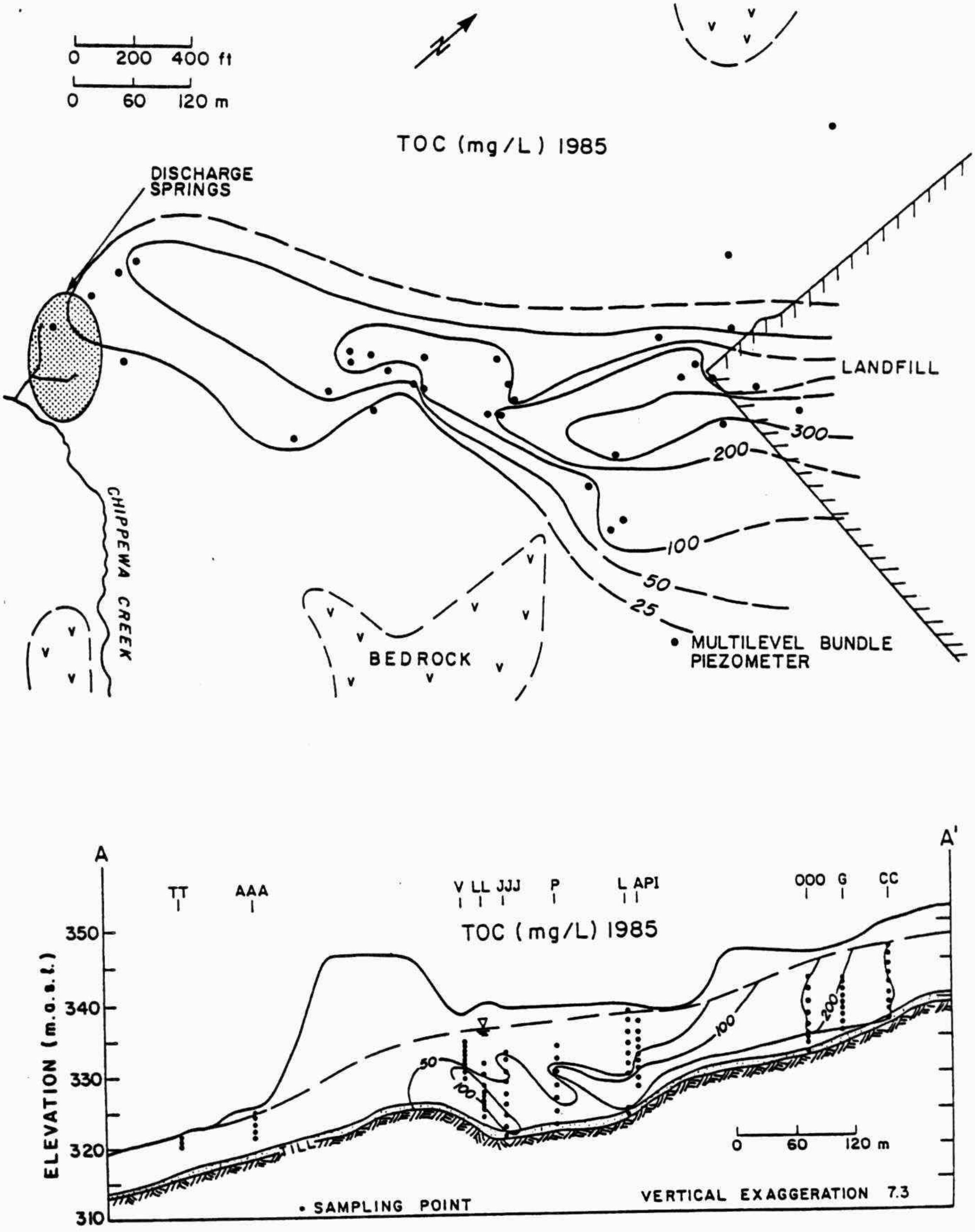

Figure 8. Total Organic Carbon , May 1985.

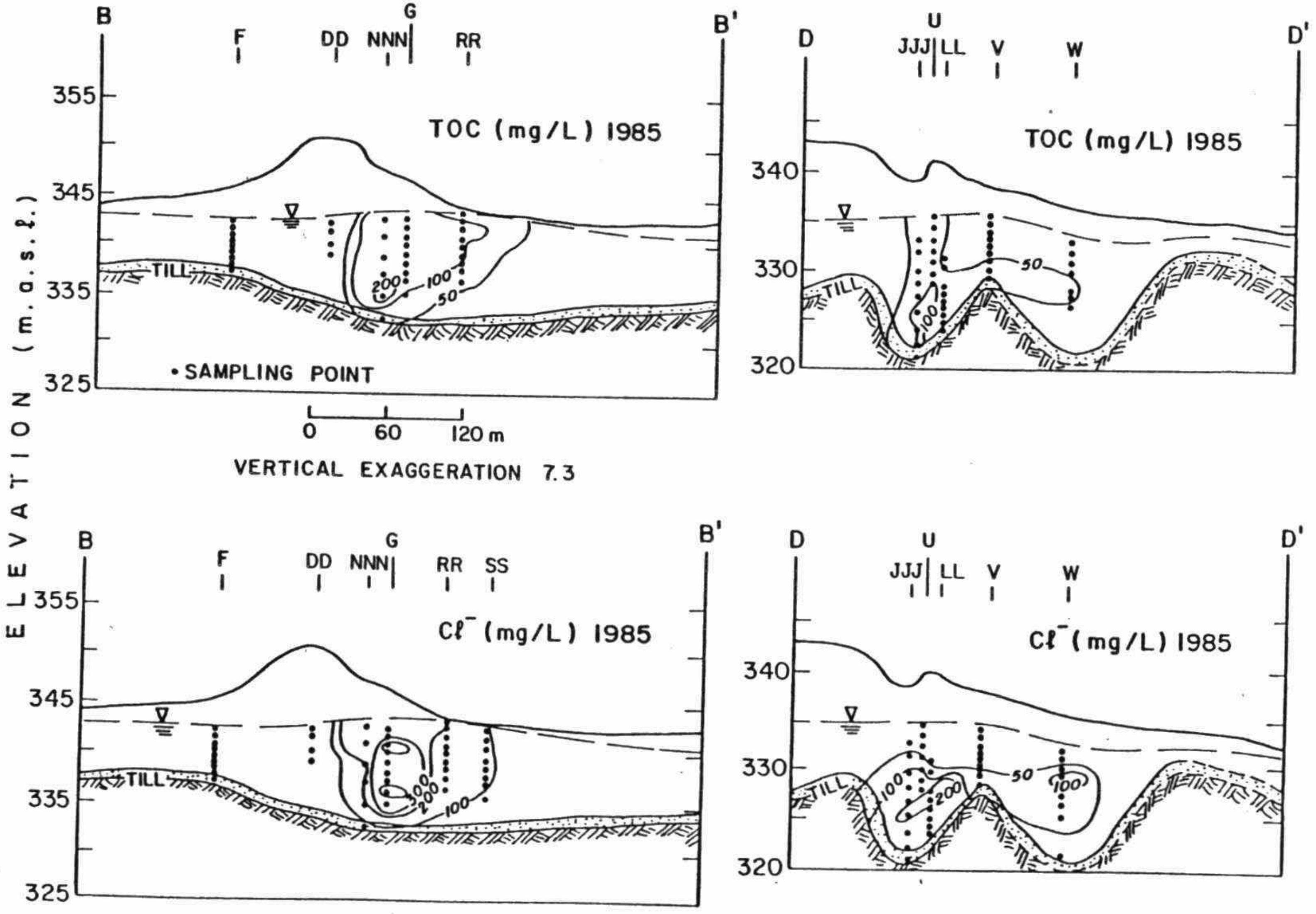

Figure 9. Chloride And Total Organic Carbon Cross Sections, August 1985.

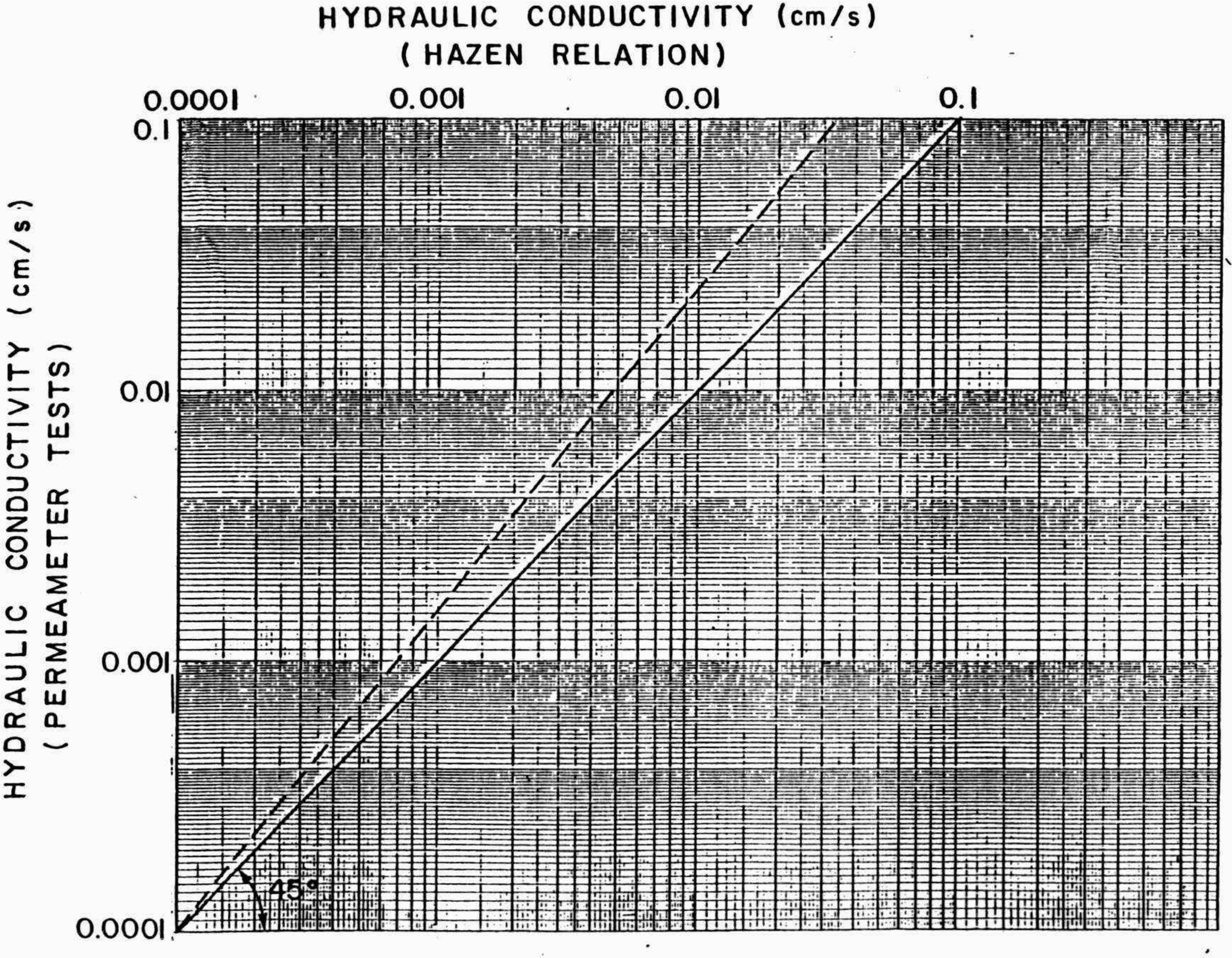

Figure 10. Comparison Of Permeameter And Hazen Hydraulic Conductivity.

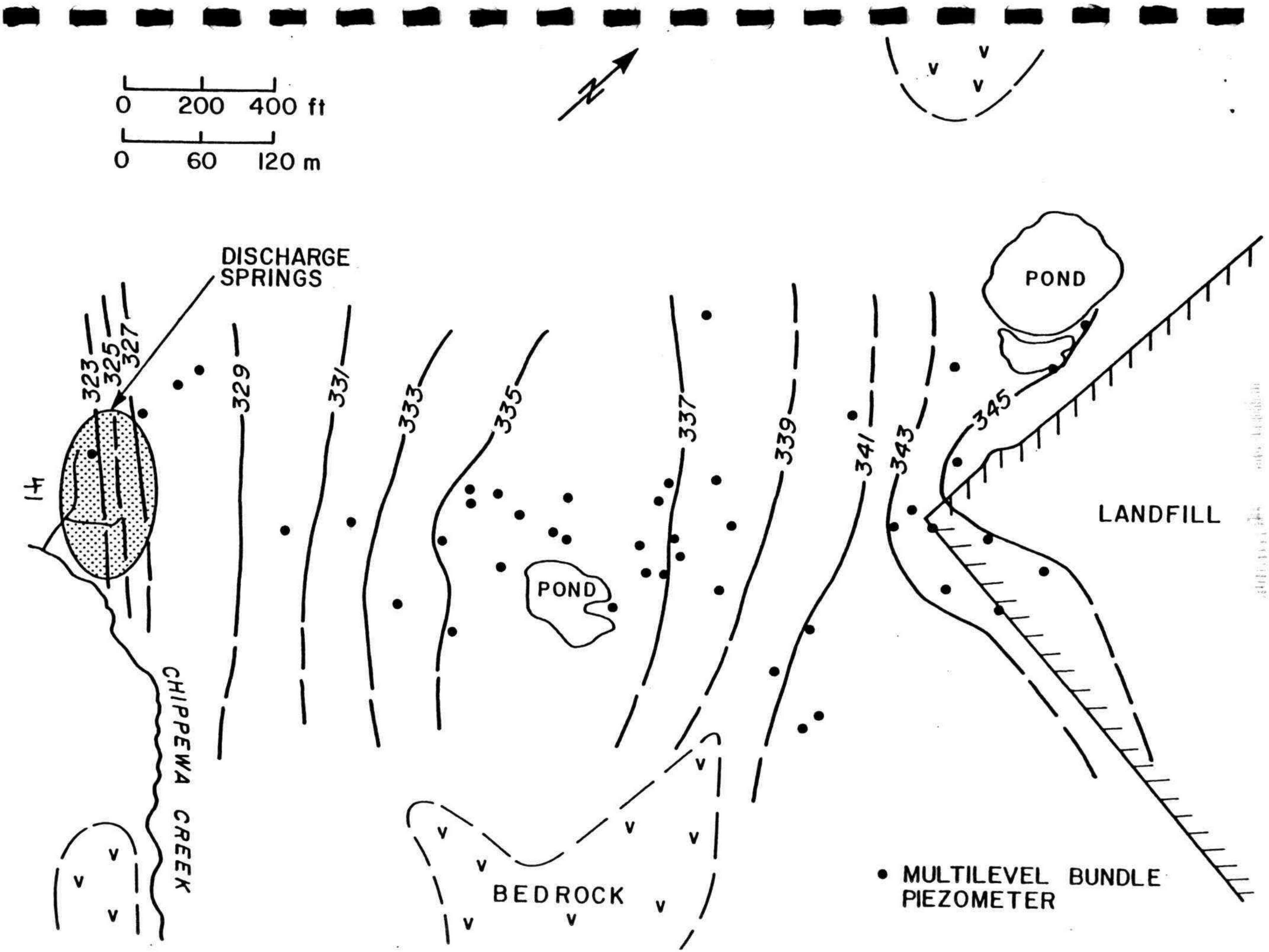

Figure 11. Water Table Map (m.a.s.l.), August 1985.

## TABLE 1

### Hydraulic Conductivity Values
### (at 8°C)

| | Permeameter Variance | Permeameter Standard Deviation | Permeameter Arithmetic Mean (cm/s) | Permeameter Geometric Mean (cm/s) | Hazen Relation Geometric Mean (cm/s) | Slug Test Geometric Mean (cm/s) |
|---|---|---|---|---|---|---|
| Zone A | 0.1778 | 0.3802 | 0.00121 | 0.00108 | 0.000545 | |
| Zone B | 0.6449 | 0.7787 | 0.0104 | 0.00698 | 0.00596 | 0.00818 |
| Zone C | 0.5385 | 0.7299 | 0.000342 | 0.000186 | 0.000123 | |

B-2

# Geophysical mapping of the subsurface at a landfill site near North Bay, Ontario

by

KHALED BEN-MILOUD

A Project
submitted to the University of Waterloo
in partial fulfillment of the
requirements for the degree of
Master of Sciences
in
Earth Sciences

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(C) Khaled Ben-miloud

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# ABSTRACT

Hydrogeologists from the University of Waterloo have for the past 5 years been investigating the movement of contaminants through an unconfined sand aquifer down-gradient of the North Bay municipal landfill site. To assist with this study, a geophysical survey was carried out at the site during a tow week period in the summer of 1984 and for one week in the summer of 1985. The objectives of this survey were:

(1) To trace the lateral extent of a contaminant plume emanating from the landfill; and

(2) To map the bedrock surface that apparently plays a major role in determining the plume's path.

About 200 VLF resistivity stations were read over a 42.0 hectare area to produce a map of the large-scale electrical conductivity patterns associated with the plume. Approximately 320 EM-31 terrain conductivity measurements were made over a two hectare area covering an intensively instrumented cross-section of the plume. The results of both these surveys are compared to groundwater conductivity measurements made by the hydrogeologists, and to models of the geophysical response. The agreement, in general, is good.

Twelve seismic lines, covering a total of 1360 metres, were completed and used to determine bedrock elevation. These data were augmented by five resistivity soundings, 55 gravity readings, and the driller's data from several boreholes.

A map of the bedrock surface is presented which confirms that the contamination plume overlies a bedrock channel. This implies that the plume's location is determined to some degree by the bedrock topography.

We conclude that the surface geophysical measurements provide a good reconnaissance-grade description of the contaminant distribution at this site.

# ACKNOWLEDGEMENTS

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I would also like to acknowledge the financial assistance received from Dr.J.F.Barker and Dr.J.A.Cherry

Lastly, but not least, I would like to thank my wife, Asya, for her encouragement and patience over the last two years.

## Chapter I

## INTRODUCTION

### 1.1 Location and history of the site

The North Bay landfill site (Figure 1.1) is situated 7 km north of Lake Nipissing in northern Ontario, about 1.9 km east of Highway 11 on March road and about 2 km northwest of the main run way of the North Bay airport.

Active landfilling of municipal refuse from the city of North Bay has been carried out on about 28 Ha for the past 19 years, and is still continuing. During that period the landfill has received domestic, commercial, solid and small quantities of liquid industrial waste from the city and from the township of North Himsworth.

The site was divided into three parts(Figure 1.2 and 1.3) according to the topography, which is very variable. The landfill itself lies beyond the northeast corner. The sand pit area is in the center. The highland areas, bounded by the escarpment, lie in the northwest of the site(Figure 1.3).

Most of the geophysical techniques were carried out on the central sand pit and on the highland areas southwest of the landfill site, based on the previous hydrogeological studies.

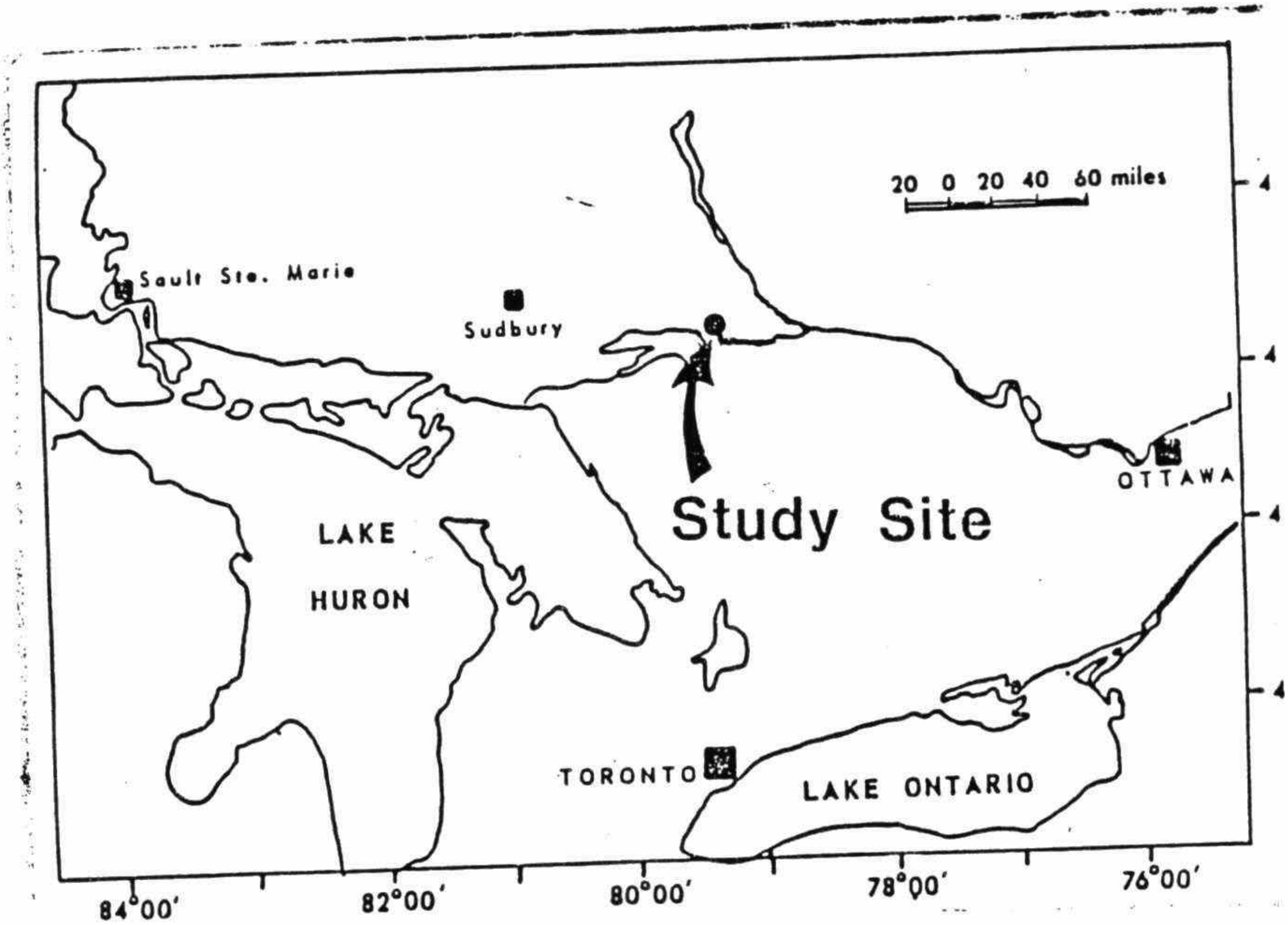


Figure 1.1: Site Location map

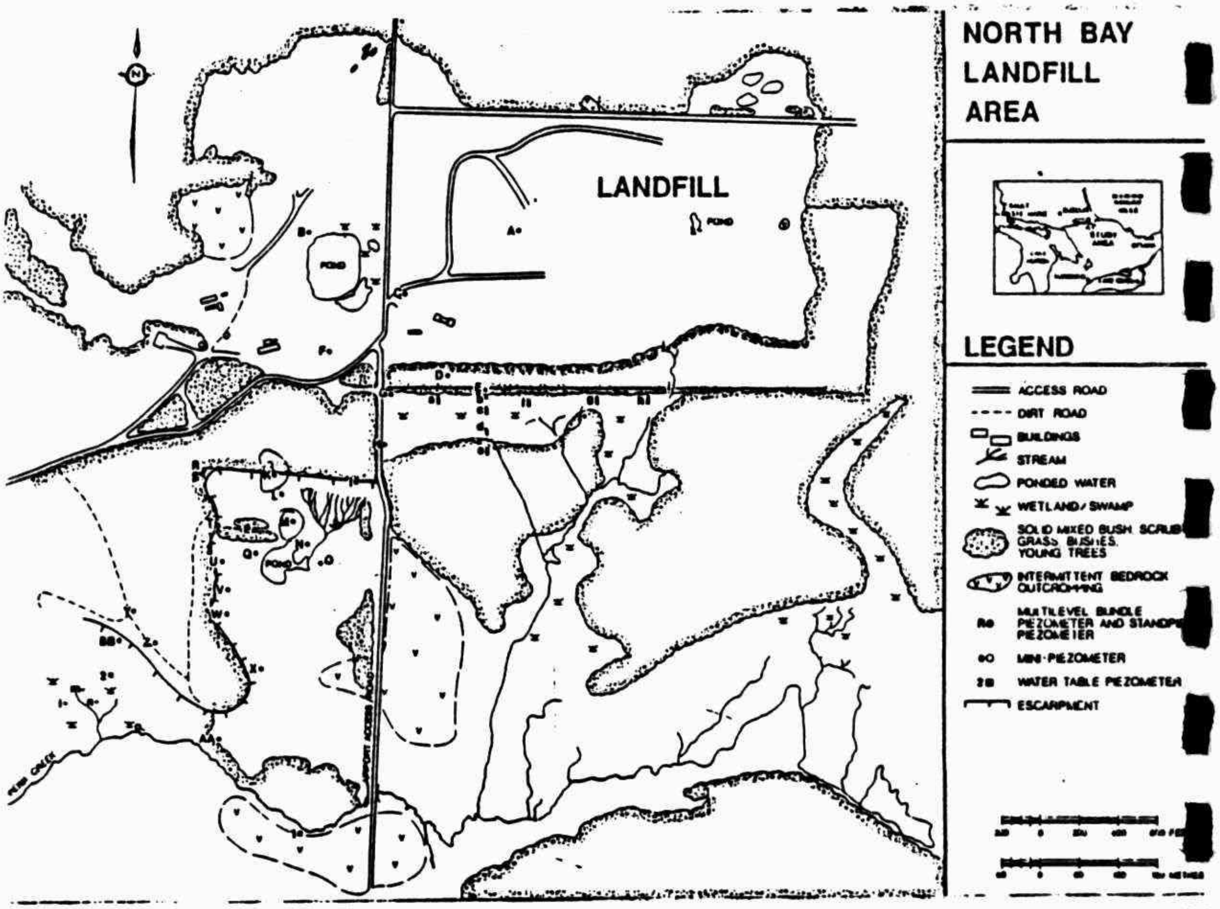


Figure 1.2: Site Plane and map of bedrock outcrops

## 1.2 Physiography

The study area falls within the northern upland physiographic region Harrison (1972). The original relief across the study site has been influenced by the extraction of sand from both the active sand pit to the west and the central sand pit to the southwest and the landfill operation.

During the summer of 1984, there was about a 20 metre range in elevations over the study area. The highest elevations were generally above 350 m above sea level (a.s.l.) in the area of active landfilling. In the central sand pit, elevations averaged 340 m a.s.l. around the vicinity of the ponds. To the west of the central sand pit,elevations on the escarpment or highland area were about 346 m a.s.l. falling to 330 m a.s.l. toward the tributary (now the plume discharge zone for Chippewa Creek).

## 1.3 Geology of the site

The area's recent geological history has been extensively studied by Lumbers (1971) and Harrison (1972). It can be summarized as follows.

The site is underlain by grey biotite gneiss, part of an extensive metamorphic complex which formed during middle PreCambrian time. The gneiss is a clastic siliceous metasediment derived from sandstones and siltstones.

In the landfill vicinity the bedrock surface is quite irregular and knobby. However, in general there is a slope to the southwest. There are three large areas of bedrock outcrop in the area (Figure 1.2), one immediately west of the landfill, and two along the eastern edge of the central sand pit. Lastly, bedrock outcrops south of the Chippewa Creek beyond the southern end of the central sand pit.

The bedrock is overlain by a thin veneer of glacial till, generally less than 1 meter thick. The till is an unstratified mixture of materials from silt to boulder size, grey in colour and characteristically very compact.

Overlying the till are grey to brown, silty sands containing some gravels. This type of deposit is widespread over the entire North Bay-Mattawa region and has been quarried extensively in the landfill vicinity for the past 25 years. The sands vary in thickness across the study site, averaging 12 meters in the landfill area, 5 metres (after quarrying) in the central sand pit and over 27 metres on the escarpment.

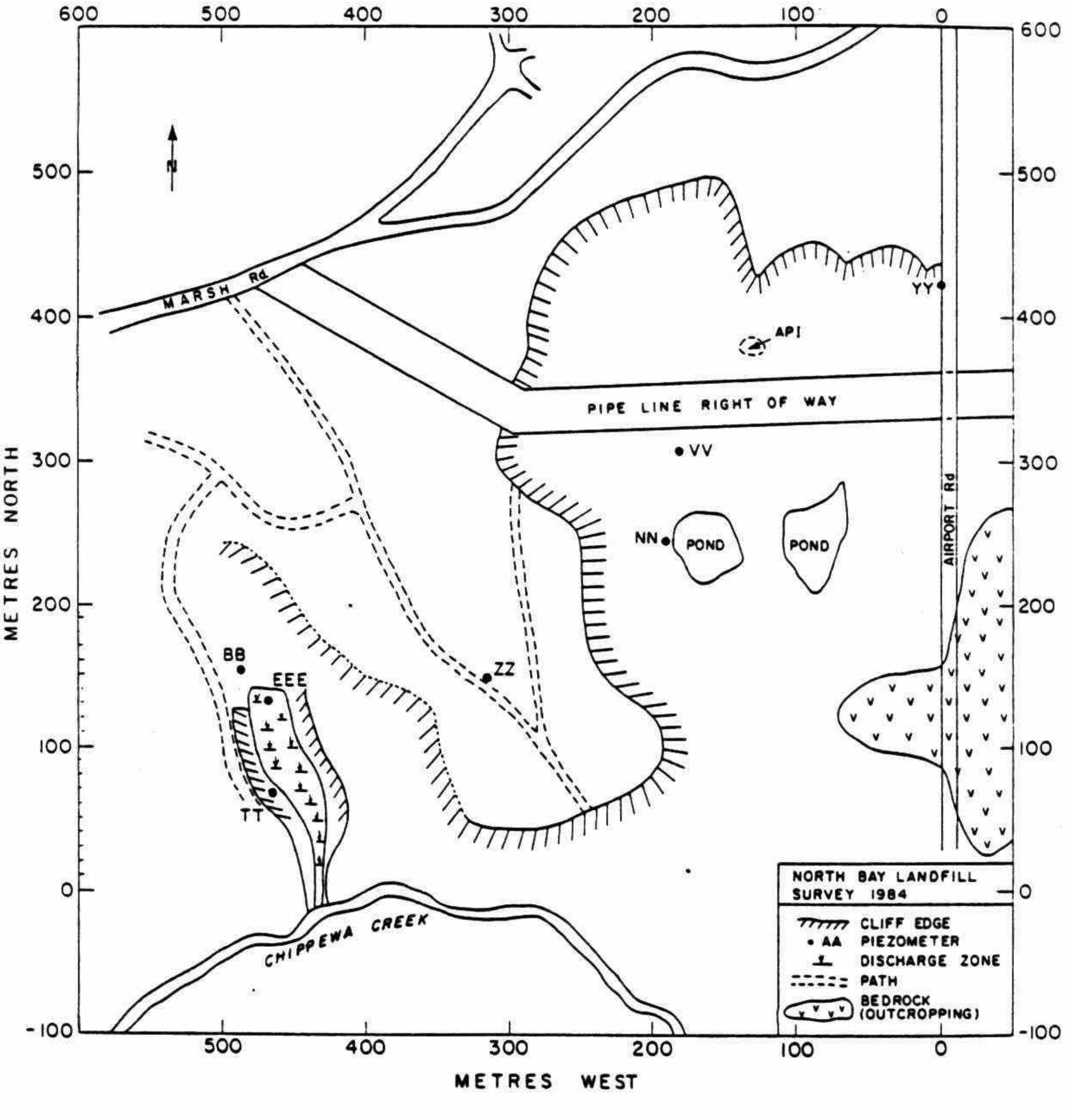


Figure 1.3: Base map ~~for the geophysical surveys~~

## 1.4 Hydrogeology of the site

Since the landfill site began operating in 1962, leachate has been seeping downward into the extensive, unconfined silty sand aquifer, and observed discharging as ponds of standing water, but mostly the water flows randomly overland eventually forming channels that flow southwest to Chippewa Creek (Figures 1.2 and 1.3).

The land between the creek and the landfill is quite wet. A distinct drainage channel runs from north to south. Water flows into the drainage channel and collects in an intermediate pond. From the pond, water drains south through the channel into the Chippewa Creek. Another wetland zone, much smaller in size, extends from the base of the escarpment to Chippewa Creek.

The water table is 11 metres below the surface of the landfill Harrison (1972). It intersects the surface of the study area at a line of the springs at the north end of the pit areas, and in the ponds. On the escarpment the water table lies about 17 metres below the ground level.

## 1.5 Ongoing research

The study of the North Bay landfill site started in 1980. An extensive network of multilevel ground water sampling devices have been established to provide a detailed, three-dimensional picture of contaminant distribution (Barker et.al., 1984).

Recent geophysical studies by Cosgrave and Greenhouse, (personal correspondence, 1985) have shown the ground penetration radar (GPR) can accurately define the lateral extent of the plume in this area. In addition disposable E-logs (DEL) (Greenhouse et.al.,1985) were installed to trace leaks and spills into the groundwater after injecting a heavy tracer (to compare the groundwater and formation conductivities).

Spatial and temporal variability of contaminant distributions have been the focus of recent studies.

## 1.6 Objectives of the geophysical work

Hydrogeological work at the site had suggested that the buried bedrock surface provided a major constraint on the lateral extent and flow direction of the contaminated ground water plume. Therefore, it was desirable to map the bedrock surface in more detail than the borehole data allowed. The extensive hydrogeological data already available on the plume's distribution provide a good test area for electromagnetic surveys designed to map plumes. With these objectives in mind, five geophysical surveys were carried out at the site during a two week period in the summer of 1984. Because more seismic data were required in areas of the site, another week was spent in the summer of 1985.

# Chapter II

# DATA ACQUISITION , PROCESSING AND MODELLING

This chapter discuses the logistics and data acquisition of the various geophysical surveys carried out, their accuracy, relative merits, and interpretation procedures.

Further details of these methods are available in standard texts, such as Telford et.al., (1976).

## 2.1 Summary of field work

Five resistivity soundings were completed over the site, at locations shown in Figure 2.3. Two hundred EM-16R VLF and 320 EM-31 stations were used to map the plume distribution. Their locations are shown in Figures 2.10 and 2.9 respectively.

Twelve seismic lines were completed, at locations shown in Figure 2.3, and 55 gravity stations (Figure 2.2) were also made in order to estimate the bedrock topography.

Well completion depths were used, in conjunction with the seismic and resistivity data, to compile a map of bedrock elevation.

## 2.2 The geodetic survey

The site was marked roughly every 30 metres over a 400 by 400 metre grid, with other points added as necessary, using a transit and 50 metre tape. Each node was assigned Northing and Westing coordinates. The original selection of coordinates at the site was made so as to be parallel to the airport road, a direction known to be almost north-south.

A leveling survey of the gravity stations was completed using the Pico 320 transit and a 4-metre survey rod. The leveling was done by taking a back-site reading on a benchmark established by the engineering staff of the City of North Bay, and by taking fore-site readings for each station along the line. The survey returned to the benchmark to close the loop.

## 2.3 The gravity survey

### 2.3.1 Equipment specifications

The gravity metre used in the survey was a Sodin Prospector Model 410. This gravity metre is basically an extremely sensitive balance measuring and indicating a change in gravity to approximately one part in 100,000,000.

The unit of measurement in gravity exploration is the milligal (mgal), where 1 mgal equals 0.001 cm/sec (approximately one part in one million of the gravity field at the earth's surface).

The mechanical drift of the gravity metre is 0.5 mgal/day, or better.

A leveling survey must accompany the gravity survey for making the Bouger correction.

### 2.3.2 Gravity corrections

The gravity metre is not an absolute instrument. It is used to measure gravity at different stations so that the gravity reading can be compared with that of a base-station or reference point.

There are three drawbacks which must be observed when carrying out a gravity survey.

(i) The readings of all gravity meters drift with time. This drift is due to tidal fluctuations and elastic creep of the springs within the instrument. As a result, readings must be made at a base-station roughly every hour in order to compensate for this drift.

(ii) The vertical gradient of the gravitational field is large and, unless corrections are made for topography, can produce anomalies far larger than those of the sub-surface features to be detected. As a result the gravity survey must be accompanied by an accurate leveling survey, and the Bouguer corrections made.

(iii) Gravity increases as we approach the poles from the equator. Therefore, a latitude correction must be made before the final gravity reading is obtained. These corrections are described briefly below.

### 2.3.3 Drift correction

Mechanical as well as tidal drift should be adequately compensated for in a gravity survey. Therefore, a gravity reading must be taken at least every hour at the base-station. The differences obtained every hour are plotted as a function of time. The drift can then be compensated for at the stations by interpolating from the "drift curve". This requires that the time at which a gravity station is occupied must always be recorded (Appendix B).

Figure 2.1 shows a typical drift curve for this survey.

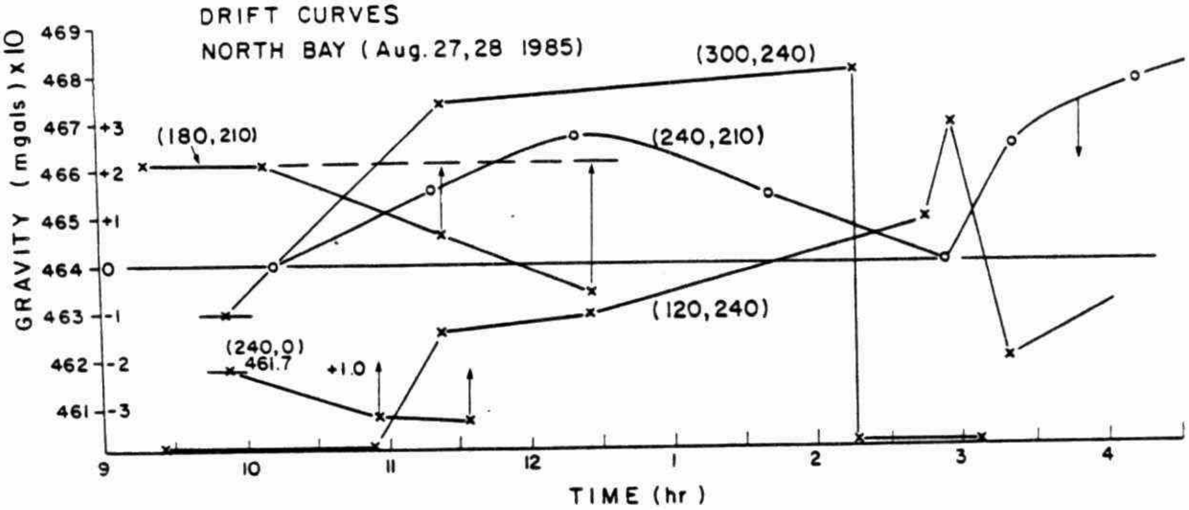


Figure 2.1: A typical example of drift curves

### 2.3.4 Free air correction

The gravitational force outside the earth varies inversely as the square of the distance from the earth's center. If g is the value of gravity at the datum level (not necessary at sea level), then at height h above datumthe gravity g is:

$$g = g \quad R^{2/(R+h)2--g}\,(1-2h/R)$$

Where R = radius of earth = 6,367 km. The approximation is reasonable if h/R higher than the first are neglected. Generally the distance of the datum level from earth's center may be taken equal to the mean radius of the earth. The correction for the elevation ("the free-air correction") is then

$$\Delta g = 2g\ h/R = 0.3086\ h \text{ mgal (for h in meters)}$$

The amount 0.3086 mgal per meter of elevation must be added to a measured gravity difference if the station lies above the datum level and subtracted if it lies below it.

### 2.3.5 Latitude correction

The earth may be considered to be an ellipsoid of revolution with an ellipticity (equatorial minus polar radius divided by equatorial radius) = 1/297. The surface of such an ellipsoid of revolution is an equipotential surface. The gradient of the gravitational potential, that is, the force of gravity (ç), is, by definition, everywhere perpendicular to the surface which means that it acts in the vertical direction. Its variation with the latitude Φ , at sea level, can be very closely approximated by the International Gravity Formula (IGF).

$$g(\Theta) = 9.78049\ (1 + 0.0052884 \sin^2\Phi - 0.0000059 \sin^2 2.\Phi)\ \mathrm{m/s}^2$$

This formula was adopted by the International Union of Geodesy and Geophysics in 1930 and is based on an absolute g-value of 981.274 cm/s measured at Potsdam by Kuhnen and Furtwangler in 1906. By differentiating equation (1) we get

λ d
δg/δ&hphi ~~=&sysb.~~: .00081 sin 2 Φ g.u./metre NS
Φ

For small latitude differences the gravity correction becomes

$$\Delta g = 0.0081 \sin 2\,\Phi\ \text{mgals.metres NS}$$

It must be subtracted from or added to the measured gravity difference according to whether the station is on a higher or lower latitude than the base station.

### 2.3.6 Bouguer correction

The free air correction presumed that the medium taking up the elevation difference between field station and base was air, whereas usually the elevation difference is taken up by rock. The rock exerts a downwards (positive) force on the gravity meter that was not taken into account by the free air correction. The Bouguer correction takes both the elevation and the intervening rock into account. Providing the ground surface is relatively smooth between base and field stations, it can be shown that the correction for the intervening rock of density $\rho$ is

$$\Delta g(\text{rock}) = 0.04191\ \rho \text{ mgals/meter (Parasnis, 1972)}$$

This correction is opposite in sign to the free air correction. The combined free air and rock correction for elevation h is then the Bouguer correction to the field station reading :

$$\Delta g(\text{Boug}) = 0.3086 - 0.04191\ \overset{\rho}{\cancel{P}}\ )h \text{ (for h in meters)}$$

and is again positive for the field station higher than the base.

### 2.3.7 Terrain correction

In most gravity surveys, the terrain in the vicinity of a station is sufficiently flat for the elevation correction to provide adequate compensation for topographic effects.

Nearby hills and valleys above and below the level of the station both give an upward component of gravitational attraction that counteracts the downward pull of the infinite slab if the topographic features causing then are sufficiently close. These topographic effects can affect the interpretation of anomalies from buried features of interest.

The correction procedure, followed here for some stations near the escarpment, is described by Dobrin (1976) (see Appendix B).

### 2.3.8 Location and techniques

Figure 2.2 shows the location of the 55 gravity stations. These stations are laid out along four lines that run east-west. The spacing between gravity stations, on each line is 30 metres, and the lines are spaced by 60 metres.

Instrument drift and tidal effects were monitored hourly at a base station. An average instrument drift (including tidal effect) of 0.021 mgal/hr was observed over the 5 days of the survey. Station elevations have an estimated accuracy of ±5 cm.

The gravity corrections, as described in sections 2.3.2-7, were made to give a final gravity reading. The value of $\rho$ , (density of sand) that was used to make terrain and Bouguer corrections was estimated by using a method from Parasnis (1976). The Bouguer anomalies at the stations on a line of measurements are calculated assuming different values of densities. The density value that shows the least correction with topography is adopted as the average density value. Expressed as a problem of finding the minimum correlation, this final density $\rho$ is given by,

It should be all on one line

$$\rho = \rho_o + \Sigma\,(\Delta G_{corr} - \overline{\Delta G}_{corr}) /$$
$$0.004191$$
$$\Sigma\,(H - \bar{H})^2$$

Where;

$\rho_o$ ~~$P_o$~~ is an initial density contrast, equal to (1.3 g/cm

$\Delta G_{corr}$ is the Bouguer anomaly,

$\overline{\Delta G}_{corr}$ is the mean Bouguer anomaly,

$H$ is the station elevation,

$\bar{H}$ is the mean station elevation.

The value of $\rho$ was set initially to 1.3 g/cm. The fairly stable$\rho$ value of 1.3 g/cm was obtained.

The final reading, in mgal, was plotted against distance in meters, and then contoured by hand to produce Figure 2.2.

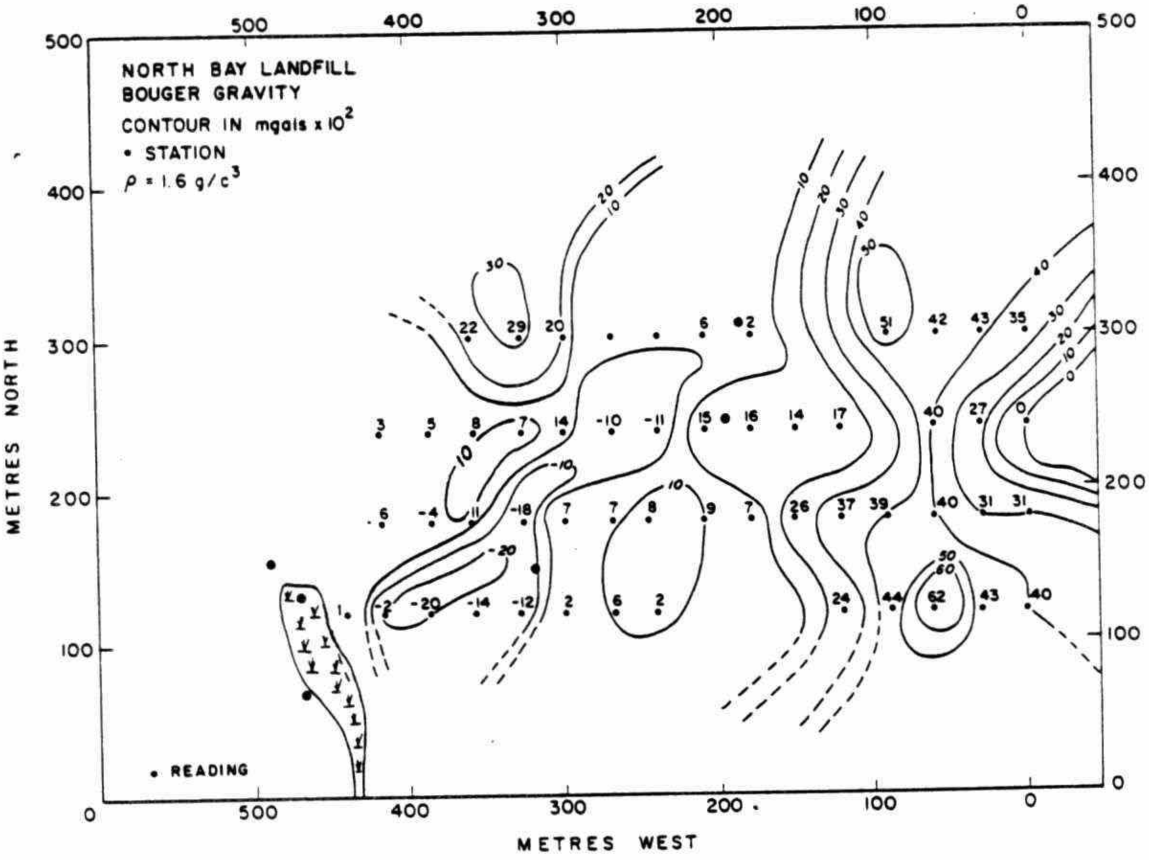


Figure 2.2: The gravity contour map

### 2.3.9 Gravity Interpretation

The gravity data have been interpreted only in a qualitative manner. The map of Figure 2.2 shows a picture which is broadly consistent with the seismic and borehole data map of borehole topography given in Figure 2.7. The gravity decreases from an eastern high area to a sharp low (corresponds in general terms with the seismic well data bedrock map) then rises slightly to the west. As we have no knowledge of regional gradients in the area, this gravity picture is hard to translate into bedrock depth, but it does seem to corroborate the existence of a bedrock channel that directs the plume movement. Further discussion of the correspondence between this map and that of Figure 2.7 will be given later.

### 2.3.10 Major sources of error

In a gravity survey, the sources of all possible errors should be well-known and their possible effect on the final results taken into account. Errors enter into all stages of data collection and processing. The error incurred while reading the gravimeter is difficult to estimate for it depends on the skill of the operator and on the amount of seismic noise in the locality. Traffic rumble and wind noise tend to agitate the delicate beam balance and the operator must settle for an average position of the survey beam. However, as the majority of readings were taken away from such noise sources, raw gravity values are considered to be accurate to at least 0.03 mgals. Close levelling survey along the individual lines indicated an average closing error of about 2 cm/km.

Using a density of 1.6 g/cm, this would produce an error of about 0.007 mgals/km in the Bouguer correction, negligible compared to other sources of error.

## 2.4 Resistivity soundings

### 2.4.1 Introduction

A Soil Test R-50 DC resistivity strata meter in conjuction with a Beckman multimeter was used to perform five Schlumberger resistivity soundings in the site (Figure 2.3).

The main purpose of these soundings was to obtain the average vertical conductivity structure and a reasonably accurate depth to bedrock (±15 percent) at minimum expense, at a few locations over the site.

A galvanic resistivity survey involves the introduction of current I into the ground through electrodes A and B. The voltage drop $\Delta V$ is measured at electrodes M and N, the wider the separation AB, the deeper the induced current penetrates. It can be shown that if $\Delta V$ is the potential difference between M and N, and I is the current induced between the electrodes AB. In a uniform medium resistivity $\rho$ is:

$$\rho app = 2\ \Pi\ K\ \Delta V / I$$

Where;

$$K = 1/AB - 1/BM - 1/NA + 1/BN$$

The value of K will vary with the geometrical arrangement of electrodes. For the Schlumberger arrangement used here,

$$K = \Pi / 4\ (AB^{2/MN})\ ,\ AB >> MN$$

### 2.4.2 Location and techniques

Figure 2.3, shows the location and the length of the Schlumberger soundings. The locations were chosen because there were no obstructions, and to sample a variety of geological environments.

Three people completed the five soundings (S1, S2, S3, S4, and S5) to spacing of 50, 45, 25, 100, and 150 metres respectively, taking about 3 hours for each sounding. The main difficulty encountered was obtaining, and maintaining, adequate electrode contact with the very dry and highly resistive surface sand. The sounding curves suffer from what could be termed an "averaging" effect, whereby topographic highs and lows on a resistivity unit (in this case, bedrock) average out the depth to the unit.

### 2.4.3 Data processing

Interpretation of the Schlumberger soundings was made as follows:

(a) $\rho$ was plotted against AB/2, on 62.5 mm log-log paper.

(b) The resulting curves were matched with 2 and 3 layers master curves, to get a preliminary model.

(c) A computer program called "INVERT", was used to adjust the preliminary model to better fit the data.

Figure 2.4, shows a typical example of Schlumberger soundings and its interpretation using the "INVERT" program.

The depths obtained from the soundings were used for the final interpretation. These depths are consistent with the depths obtained from either the boreholes or the seismic data.

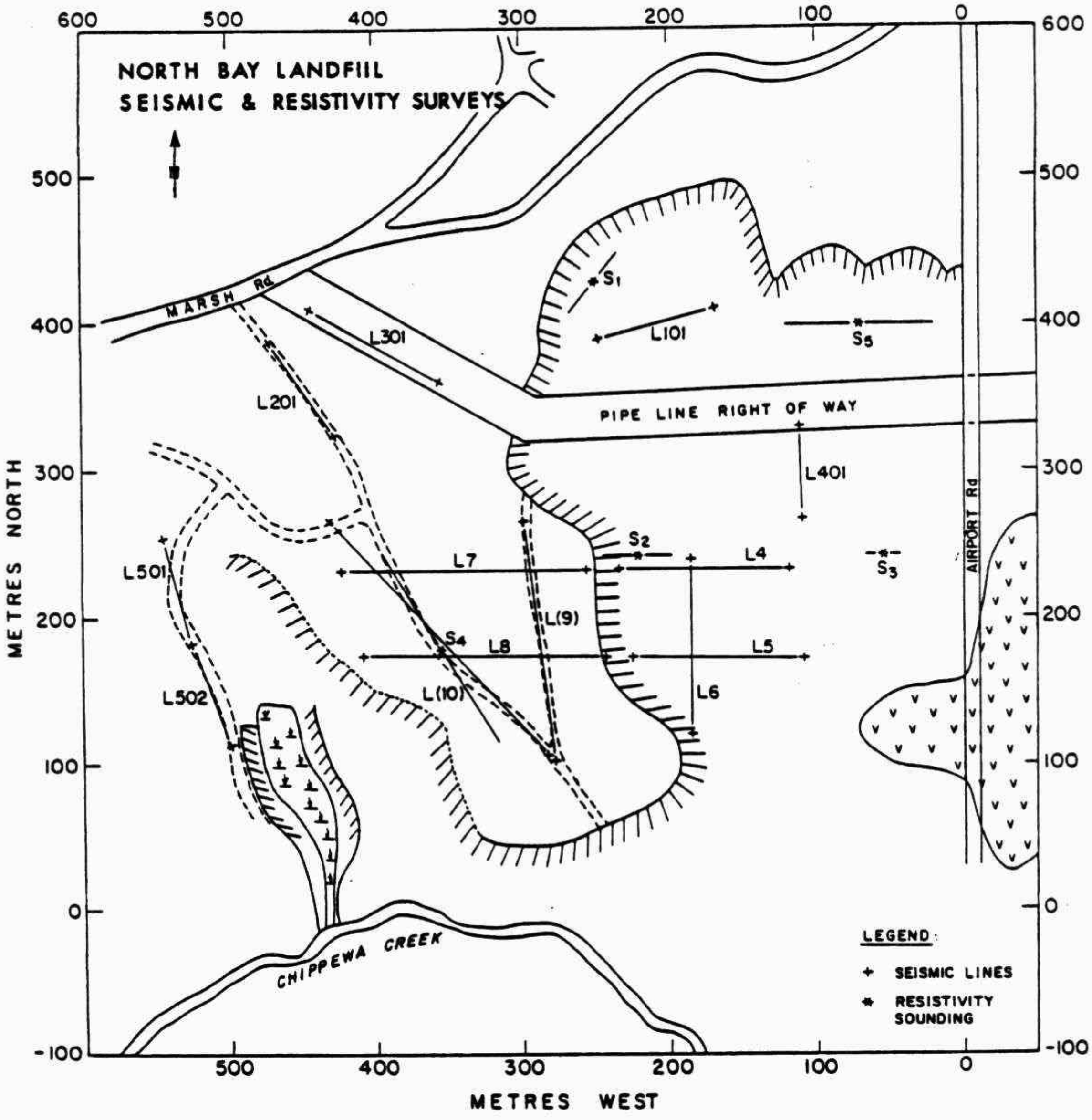


Figure 2.3: Base map for the seismic and resistivity surveys

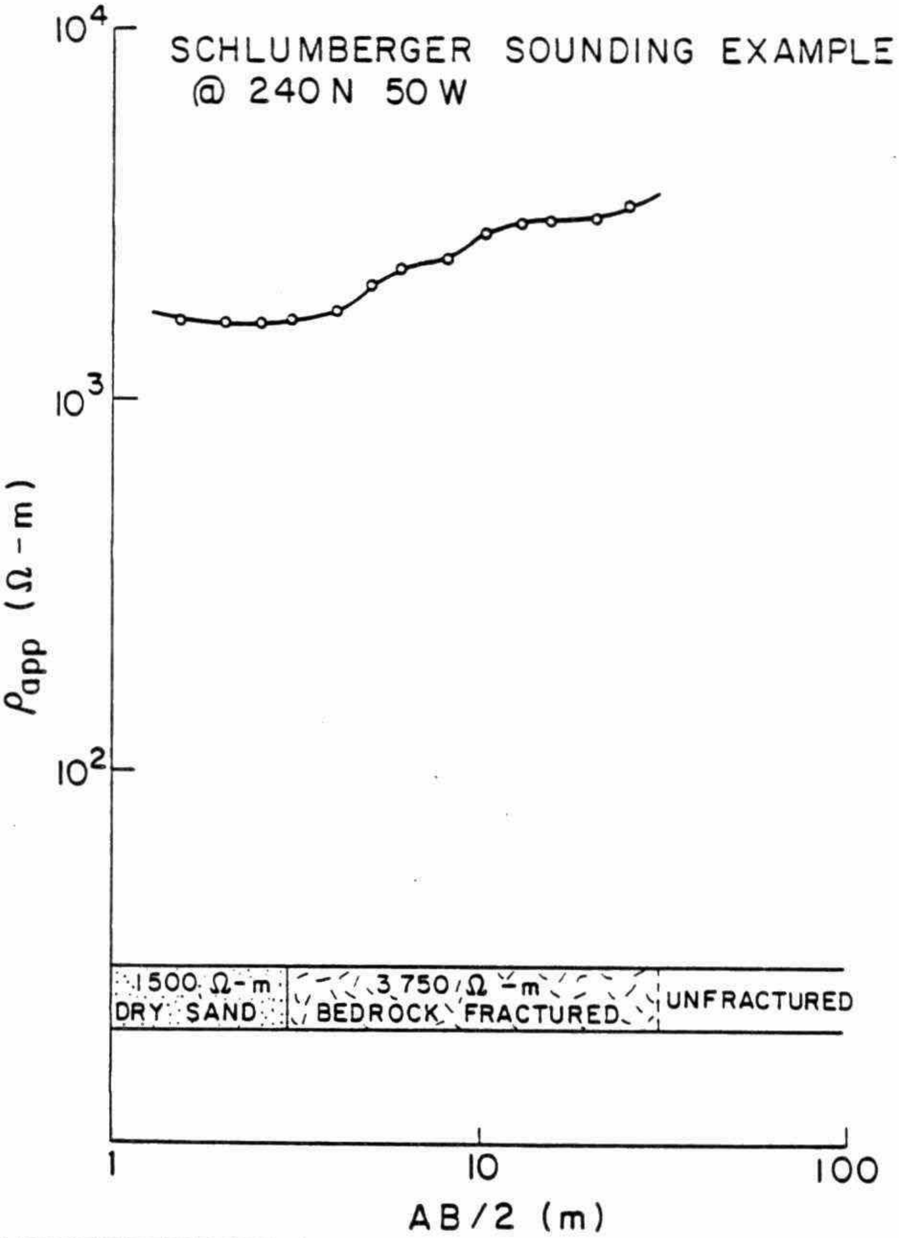


Figure 2.4: Schlumberger sounding S3

### 2.4.4 Major sources of error

The soundings S2 and S4 (Figure 2.3) could not be matched by plane, horizontal layered models. Because of these problems the curves were discarded.

## 2.5 Seismic refraction survey

### 2.5.1 Theory

Seismic refraction, an important technique in ground water exploration, consists essentially of generating seismic waves at a "shot point" and timing their arrivals along a spread of detectors or "geophones".

By knowing the travel-time to the various geophones and the velocity of the waves, it is possible to reconstruct the path of the seismic waves and derive subsurface structural information.

The velocity of seismic waves is dependent upon the "hardness" or degree of consolidation of the geologic deposit. The more consolidated a deposit is, the faster the velocity of seismic waves will be Telford et al., (1976). Thus, there will be a very distinct contrast between the velocity at which seismic waves travel through sands, and the velocity at which they travel through bedrock. Another important aspect is that the direction of motion of the propagating wave will change at an interface between different geologic materials; that is, the wave is refracted along a new path.

### 2.5.2 Location and techniques

A 12-channel refraction seismic graph, the Nimbus 1210F, was used to collect the seismic data (Appendix D). This instrument is equipped with a recording oscilloscope with two millisecond timing lines. It also includes a blaster with timing delay circuit. Power is supplied by a 12 volt D.C. battery. Twelve seismic lines were measured over the site, to find the depth to bedrock. Their locations are shown in Figure 2.3.

The geophone spacing used was 3, 6, 10, or 15 metres, depending on the sub-surface conditions and to what depth we were sounding. The 3 metre geophone interval was used with hammer shots on almost all seismic lines, to estimate the velocities of the uppermost layer. All dynamite shots were detonated 1.0 metre off the line and about 0.85 metre below ground-level to minimize blast damage and to ensure maximum energy transfer into the earth.

The off-end shots were varied in their distance away from the nearest geophone to assure first arrivals from the bedrock refractor. Standard electrical blasting caps were used as the rapid-fire seismic caps (made specially for this purpose) proved to be too expensive. The approximate 6.0 m/sec delay involved in using the standard caps was overcome by placing a start geophone next to the blast (approximately 1.0 metre away) and by comparing times to a 10.0 metres distant geophone with that obtained from a hammer blow where no shot delay occurs.

The three seismic lines run in 1985 used an OYO McSeis-1500, seismic system with diskette recording.

By measuring the arrival times of waves which travel through different materials, at increasing distances from the wave source, the thicknesses of subsurface layers can be calculated.

The data collected from dynamite and hammer sources were plotted on a time-distance plot. A typical example can be seen in Figure 2.6, which shows the velocity of the upper unsaturated sands to be 400 m/sec, the velocity of saturated sands 1500 m/sec, and the velocity of the bedrock 5000 m/sec. Also marked on the field record of Figure 2.5 is the geophone number for each trace, the spread number, the location and the size of the shot, plus the time of the blast. These velocities and intercept times derived from the time-distance plot were used in a program called "Dipper" to calculate the depth and the dip of the bedrock, when plane layered solutions were appropriate. In other areas, where an irregular bedrock surface was evidently present, the Plus-Minus theory of Hagedoorn (1959) was used. The elevation and grid loction of each geophone were stored in a DEC.PRO.350 micro-computer hard disk file. The depth to bedrock at each geophone was then computed using a spread sheet program. The results are listed in Appendix D.

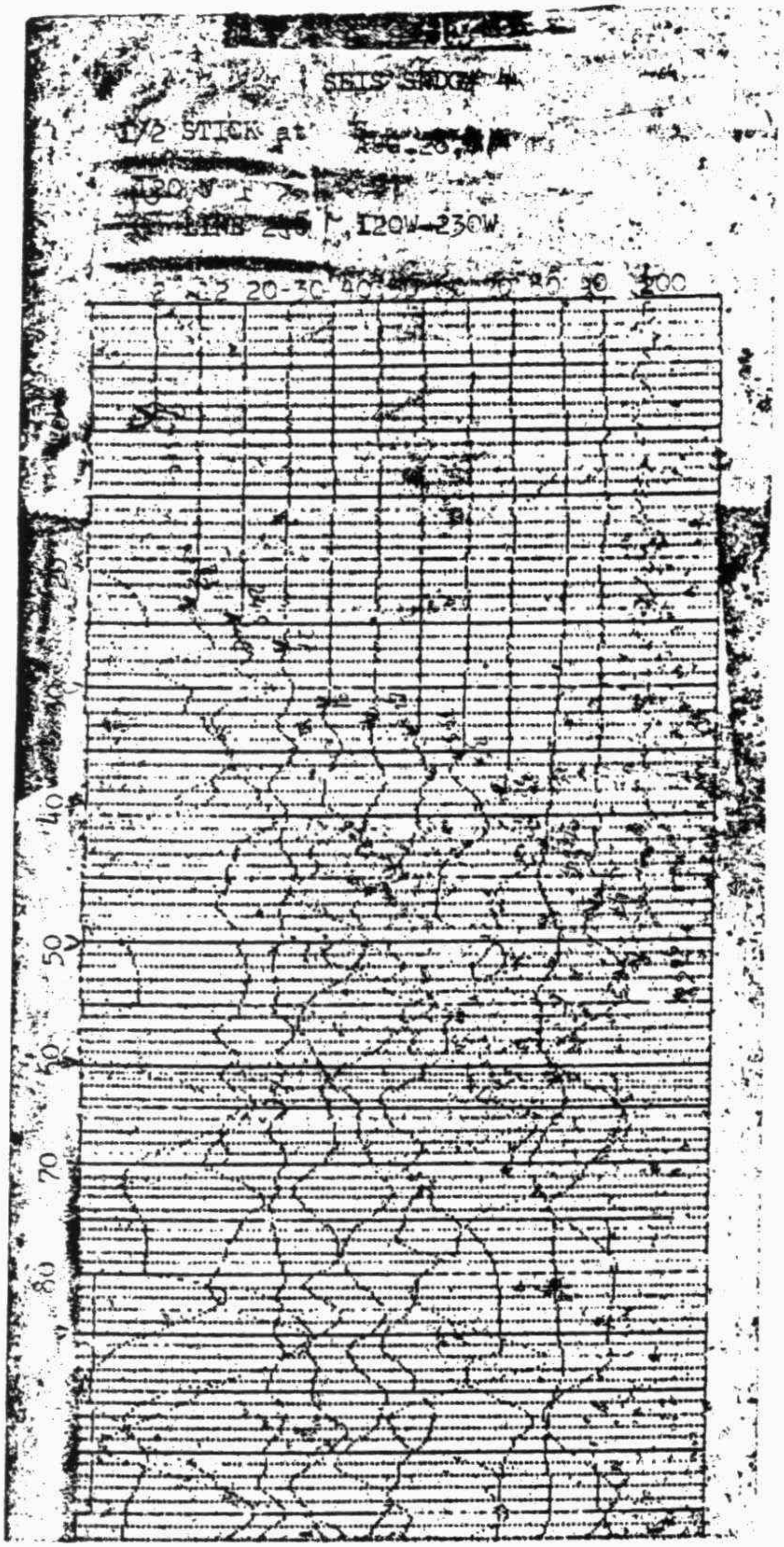


Figure 2.5: An example of a seismic record

### 2.5.3 Bedrock depth from drilling and seismic data in the study area

Many wells were drilled in the site (Figure 1.2), but not all of them reached the bedrock surface. Only the wells labelled "BB", "EEE", "AA", "H", "R&S", "O", "M" , and "T" reached the bedrock surface. In Figure 2.7 the wells which reach the bedrock surface are denoted by a full circle, while those denoted by an empty circle do not.

There is a fairly good agreement between the bedrock depths from wells and the depths obtained from seismic data. Using the surface elevation of these wells and seismic station, a map of the elevation or the bedrock surface has been attempted Figure 2.7.

All the depth data are stored in a CMS file called "NORBAY BED" (see Appendix E), including coordinates, surface elevation and bedrock depths. The contouring was done by hand due the difficulty of machine contouring the unevenly distributed data points in some parts of the site. The contour interval was selected to be 3 metres. Figure 2.7 shows the bedrock topography to slope inward to a low of 325 m a.s.l. west of central sand pit, rise slightly and then fall again to 313 m a.s.l. around the discharge area. West of the discharge area the contours are drawn as dashed lines, which close around the bedrock low as suggested, but not really confirmed, by the gravity and VLF data.

These bedrock depth data where also stored in an IBM personal computer file called "NORBAY BE" and contoured in three-dimensions Figure 2.8, using a routine called "SURF" from Golden Software Inc. The "view" in Figure 2.8 was taken from an altitude of 38°, above the discharge site. The three-dimensional view includes a lot of interpolation by the computer software; nevertheless, the picture clearly shows a bedrock depression linking the source and discharge zones, and this we believe to be substantially correct.

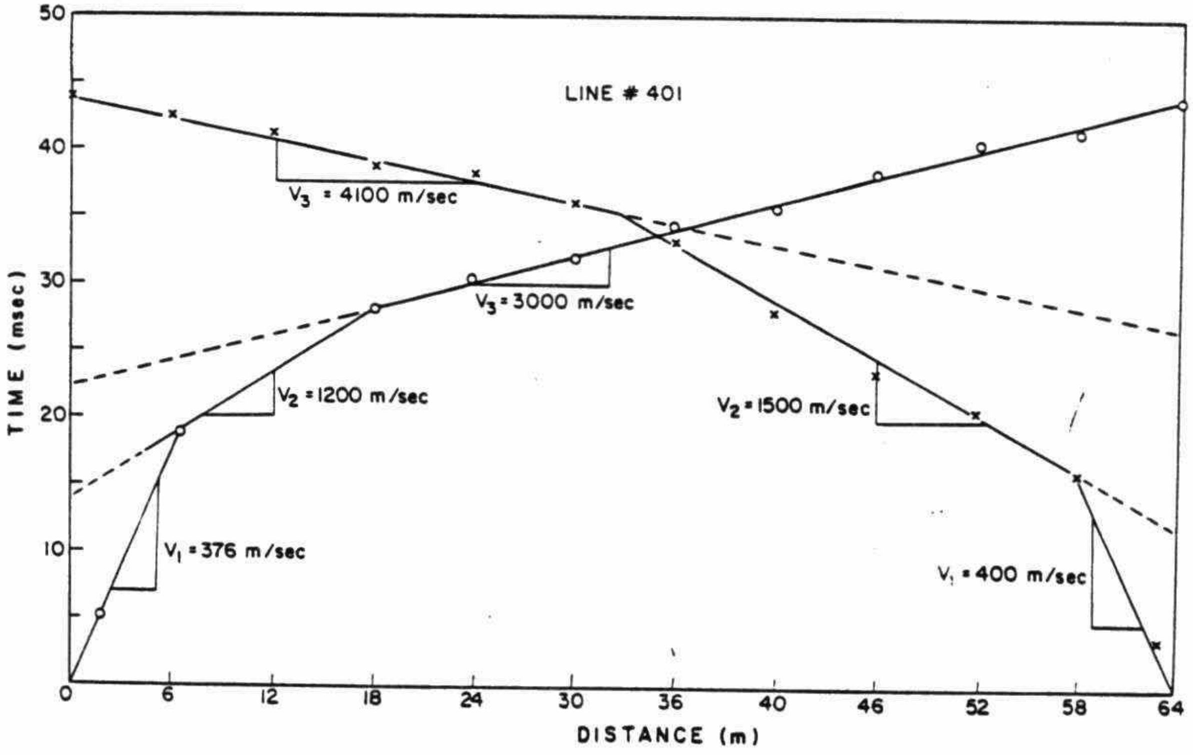


Figure 2.6: An example of a Time- Distance plot

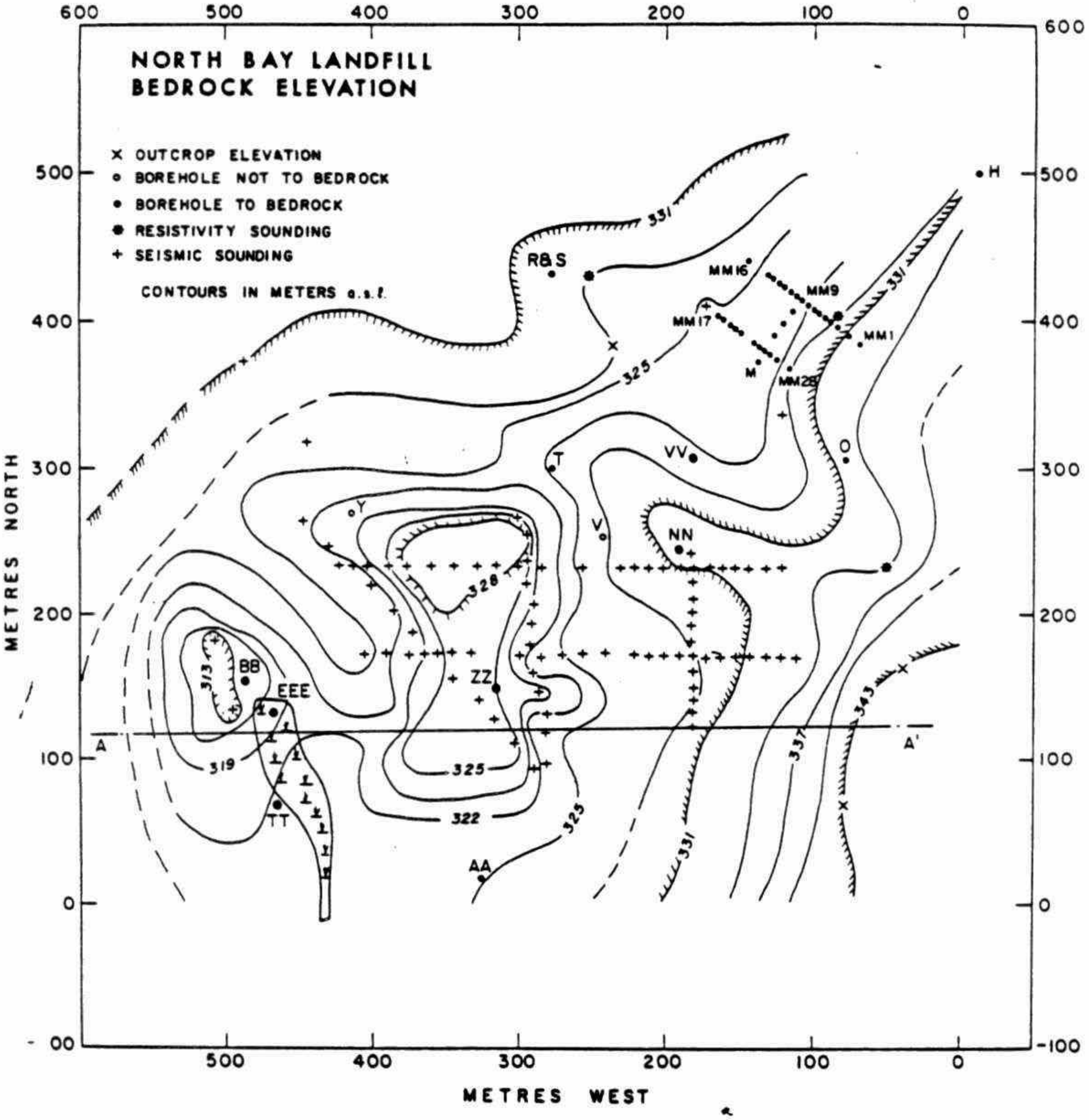
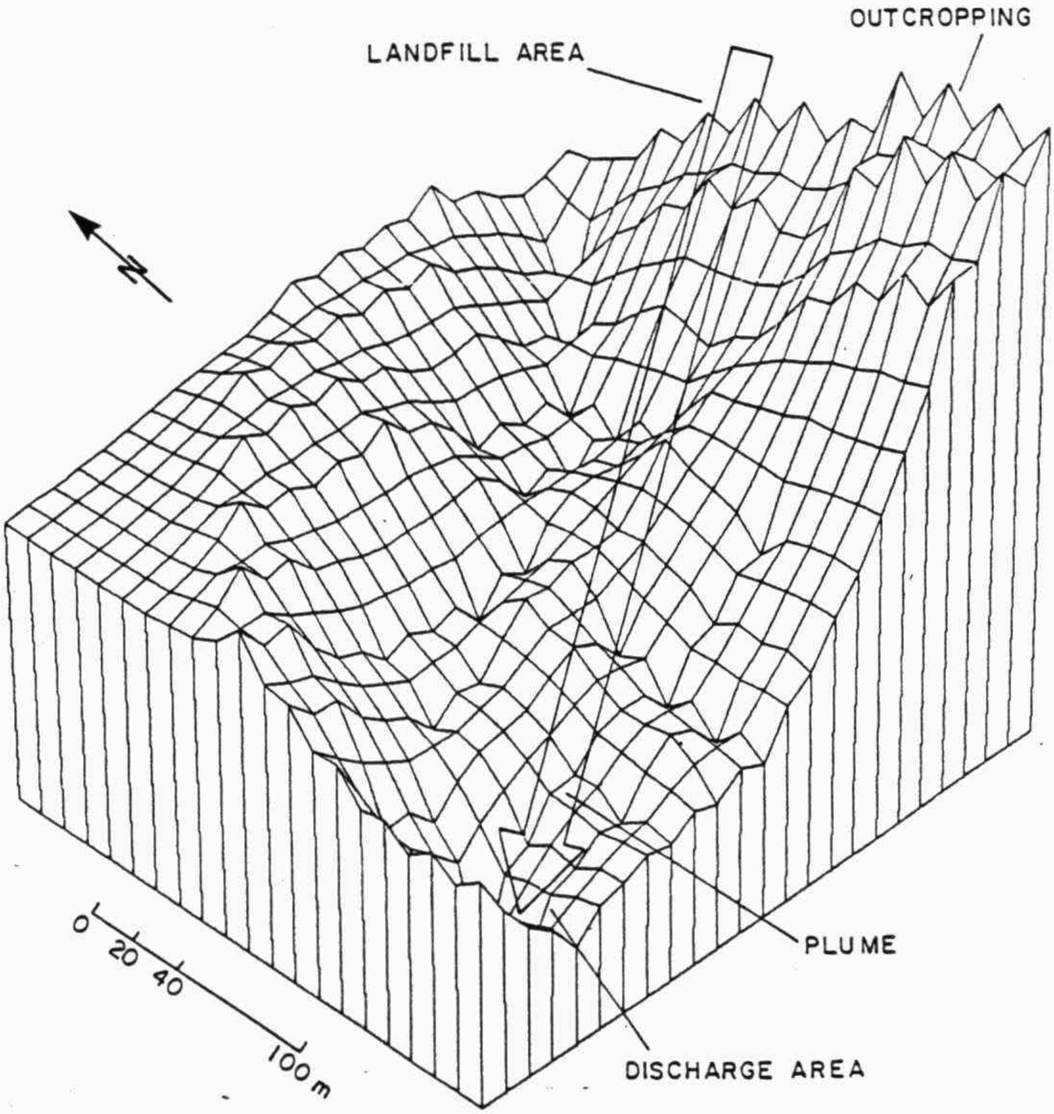


Figure 2.7: Bedrock contour map from seismic, resistivity and borehole data



BEDROCK VIEWED FROM DISCHARGE

Figure 2.8: Three-dimensional view of the bedrock topography

## 2.6 Inductive resistivity measurements

### 2.6.1 Theory

Electromagnetic resistivity surveys involve the propagation of low-frequency, time-varying electromagnetic fields in the ground. The equipment includes a transmitter coil (Tx), and a receiver coil (Rx) separated by a short distance, s. The transmitter coil, energized with an audio frequency alternating current, is placed on the earth surface. This creates a time-varing magnetic field (Hp), which penetrates the ground, inducing low currents in the ground conductors it encounters. These currents generate a secondary magnetic field (Hs) which is sensed, along with the primary field, by the receiver coil. Hs is a function of the frequency, the distance between Tx and Rx, and the ground conductivity. These instruments generate many fields at frequencies such that the skin depth is considerably larger than the depth of interest, (called operating at "low induction number"). Under this condition, the ratio of Hs/Hp is linearly proportional to the conductivity of a uniform, homogeneous earth. The EM instrument then becames a direct reading, linear terrain conductivity meter. The apparent conductivity induced by the instrument is defined as :

$$\sigma app = ( 4/2 \Pi f \overset{\mu}{M} S) (Hs/Hp)$$

where;

$\sigma app$ = apparent conductivity (mmhos/m), f = frequency (Hz)

$\mu_{\circ}$ M = permeability of free space

S = distance between the coils (m) (McNeil , 1980)

Conductivity is measured in millisiemens per metre (or millimhos per metre). The EM-31 unit was selected because it is simple to use, requires only one person as operator and does not requires ground contact. It can accurately measure small changes (5-10 percent) in conductivity over a range of 10 to 1000 mS/m. However, at lower value of terrain conductivity, it becomes difficult to magnetically induce enough current into the ground to produce a detectable signal at the receiver coil. Another disadvantage is its limited effective depth of penetration, roughly equal to the coil separation.

The particular instrument used in this survey was the Geonics EM-31, with a coil separation of 3.7 metres.

### 2.6.2 Location and techniques

EM-31 surveys were generally carried out with five and ten metres stations spacings, and in a small area in the north eastern part of the site Figure 2.9. The objective was to determine lateral extent of the contaminant plume in some detail. The instrument was operated in the vertical mode, with an effective depth of penetration of about 4.0 metres.

EM-31 raw data (Appendix C), including location and elevation of each station, were stored in a CMS file called "NORBAY EM-31". This file was submitted to a WATFIV program called "TRANS" which organizes the data for input to the SURFACE II contouring program.

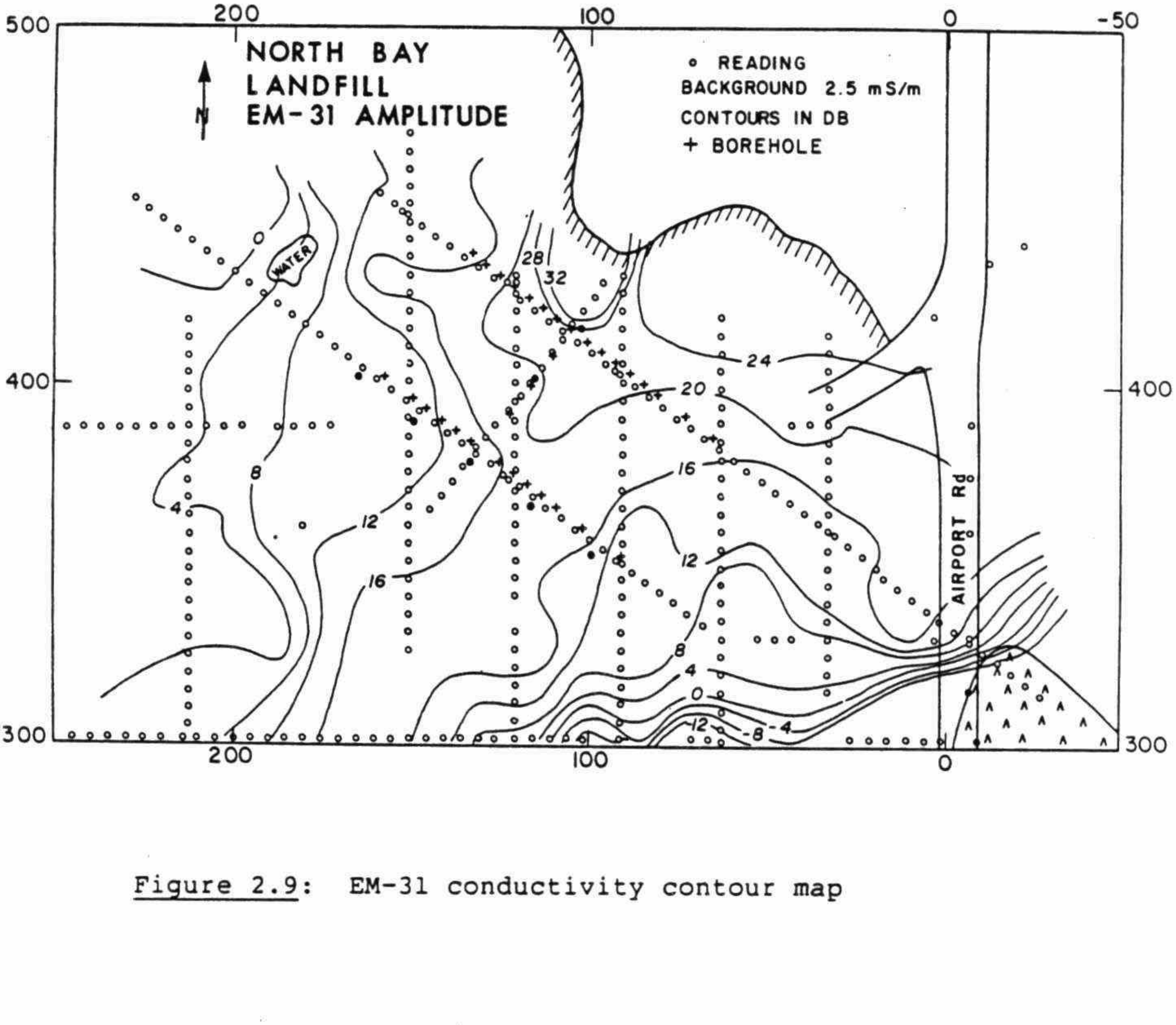


Figure 2.9: EM-31 conductivity contour map

### 2.6.3 Data processing

The SURFACE II Contouring program, developed by the Kansas State Geological Survey (Sampson 1975) was used to produce the EM-31 conductivity contour map of Figure 2.9. Decibel (DB) units have been adopted to give convenient whole numbers; the contour interval was selected to be 4 DB, where

$$DB = 20 \log (\sigma app(x,y)/\sigma app\ B)$$

and the terms, $\sigma app(x,y)$ and $\sigma app\ b(x,y)$stands for any given reading on the grid and an average background conductivity value respectively. The background conductivity was estimated to be 2.5 mS/M, from readings away from the plume where uncontaminated water lay close to the surface.

## 2.7 VLF-resistivity measurements

### 2.7.1 Theory

The Geonics EM-16R meter used in this study uses electromagnetic energy induced in the ground from distant, very-low-frequency (VLF) transmitters to estimate the conductivity and thickness of overburden cover, and to detect anomalous conductivity zones within the overburden. The unit obtains its primary signal from one of a number of powerful VLF radio transmitters situated around the North America. The station used in this survey was usually NAA at Cutler , Maine, broadcasting at 17.8 KHz.

Faraday's law states that an electrical field must exist in the vicinity of a time-varying magnetic field. The EM-16R measures the ratio and phase of the horizontal magnetic and horizontal electrical field components of these fields

From the theory of wave impedance, it can be shown that for a wide range of practical conditions and over homogeneous ground of conductivity ρ, that

$$\rho = Ex/Ey\ (1/2\ \Pi\ f\ \overset{\mu}{\cancel{M}})$$

Where

$\rho$ is ground resistivity (ohm-m),

Ex is the potential gradient along the ground (Volts/metre),

Hy is the horizontal magnetic field strength (Amps/metre),

f is frequency (Hz),

$\overset{\mu}{\cancel{M}}$ is the permeability of the ground (Henries/metre)

The operating procedure of the EM-16R is described in the instrument manual, so it will not be dealt with here.

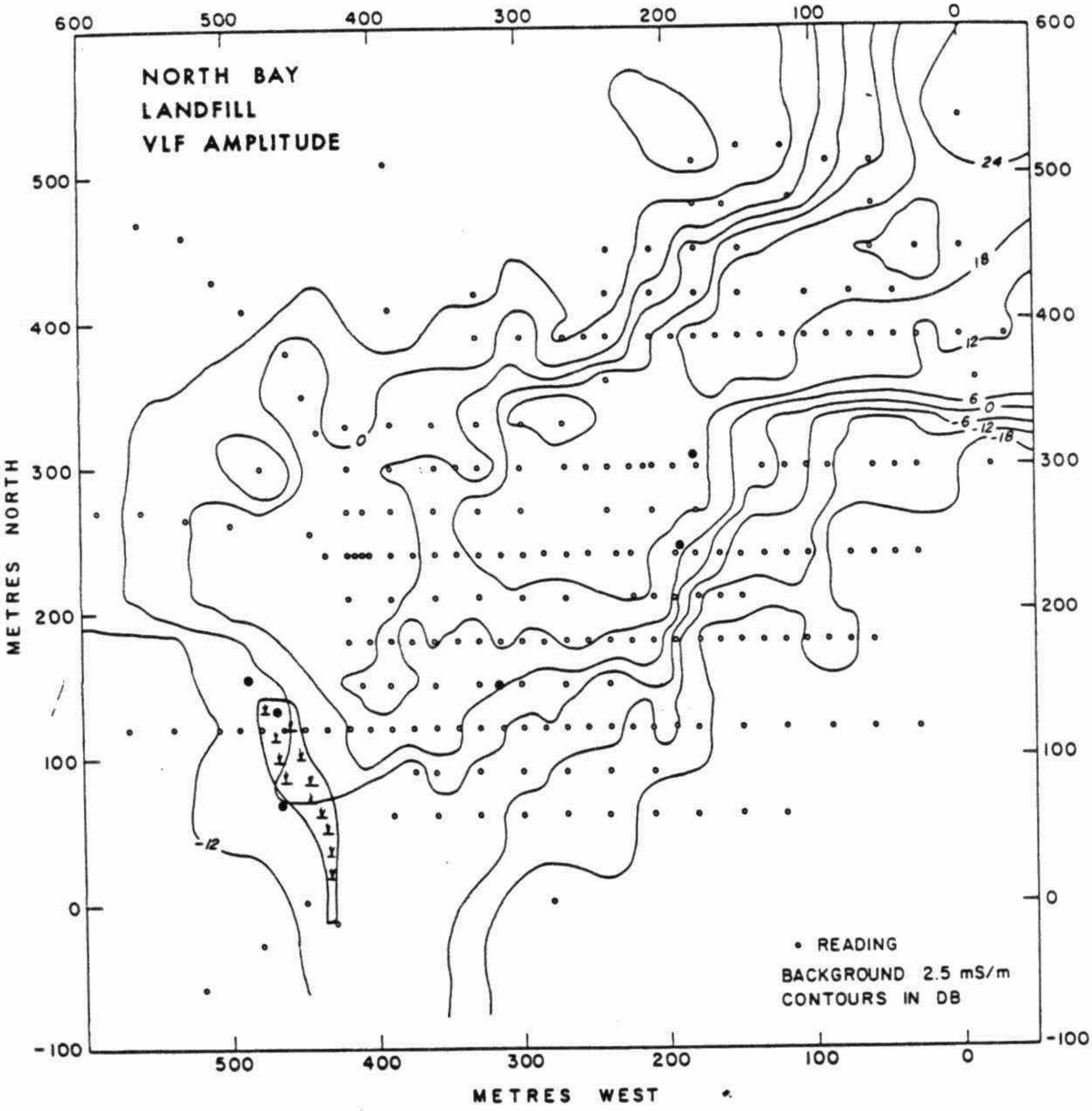


Figure 2.10: EM-16R VLF conductivity contour map

### 2.7.2 Location and techniques

The survey completed for this report consisted of 200 stations taken throughout the site (Figure 2.10). Stations were placed at 30 metre intervals along the major eastwest lines and also fitted in as necessary as the pattern of contamination developed.

The collected data from the site as well as the location and the elevation of each station were stored in file called "NORBAY VLF" (Appendix C).

The contouring was accomplished by inverting the data from resistivity to conductivity, normalizing with the TRANS program, and then submitting it to SURFACE II.

### 2.7.3 Data processing

The same contouring procedure was used as for the EM-31 data, with a contour interval of 6 DB.

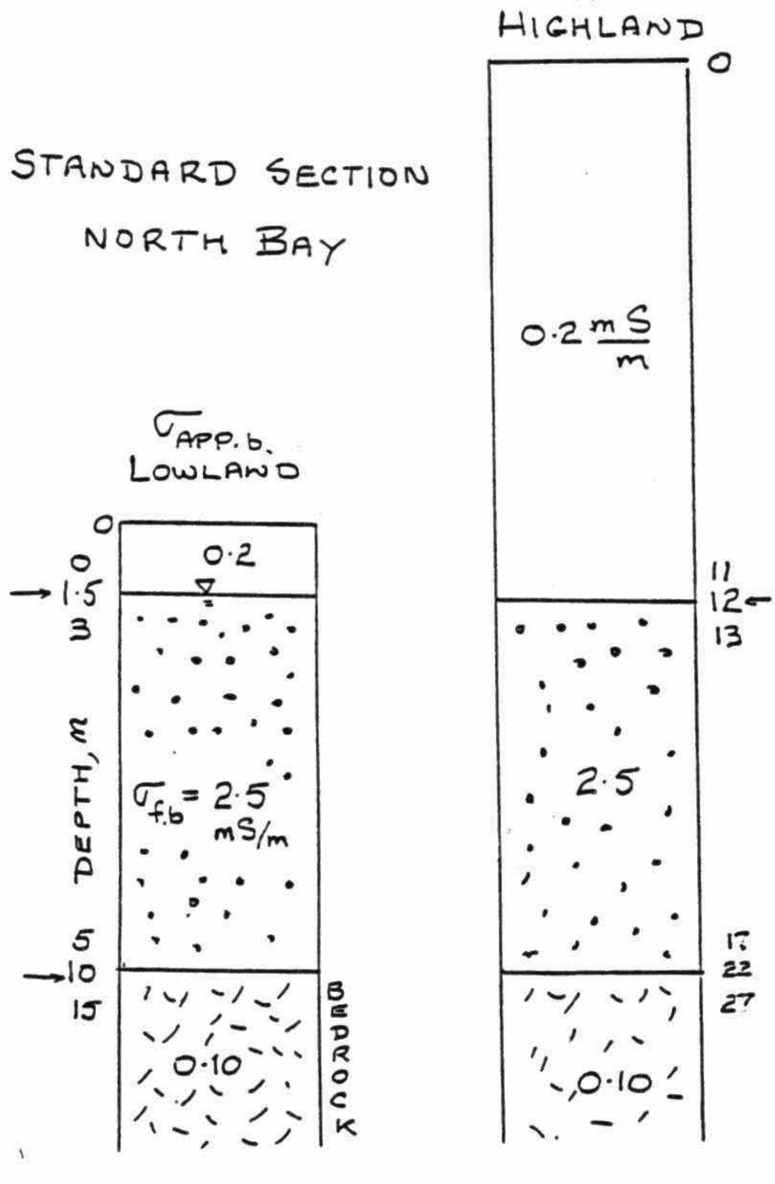


Figure 2.11: Standard sections at the North Bay site for the base(left) and top of escarpment. Layer thicknesses are given beside columns in metres, conductivities in mS/M.

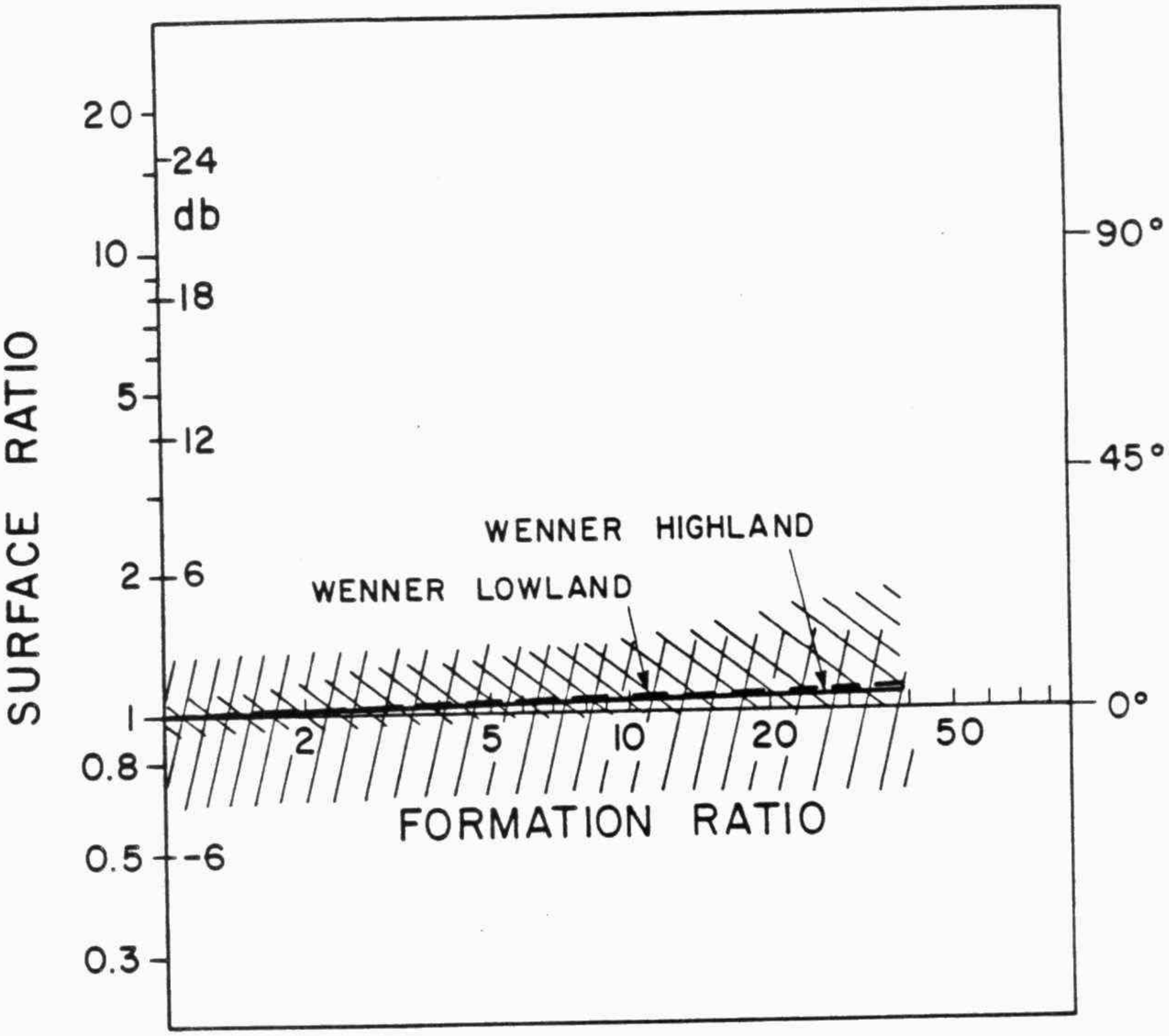


Figure 2.12: Wenner prediction curves

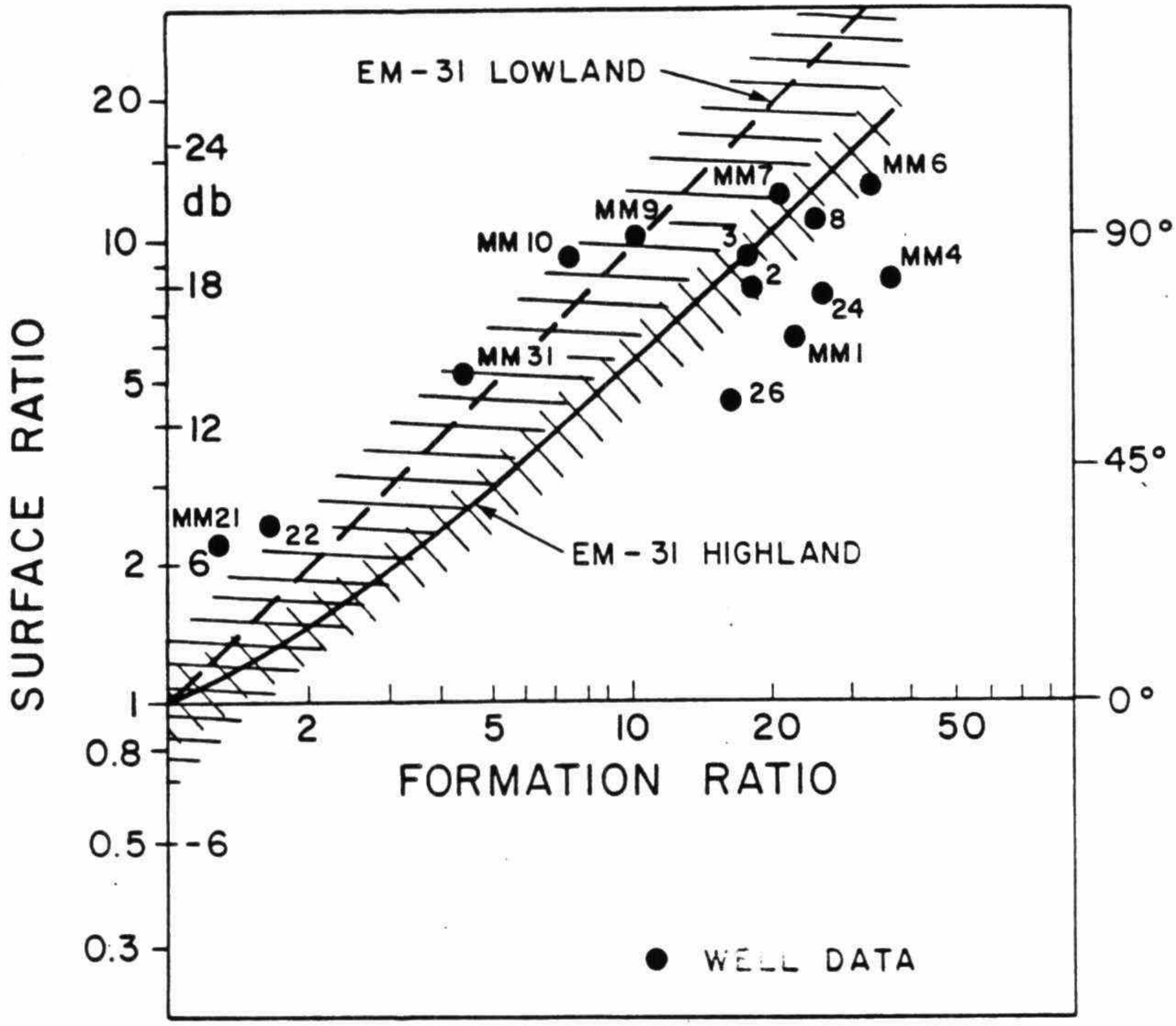


Figure 2.13: EM-31 prediction curves and measured average groundwater conductivities in the wells

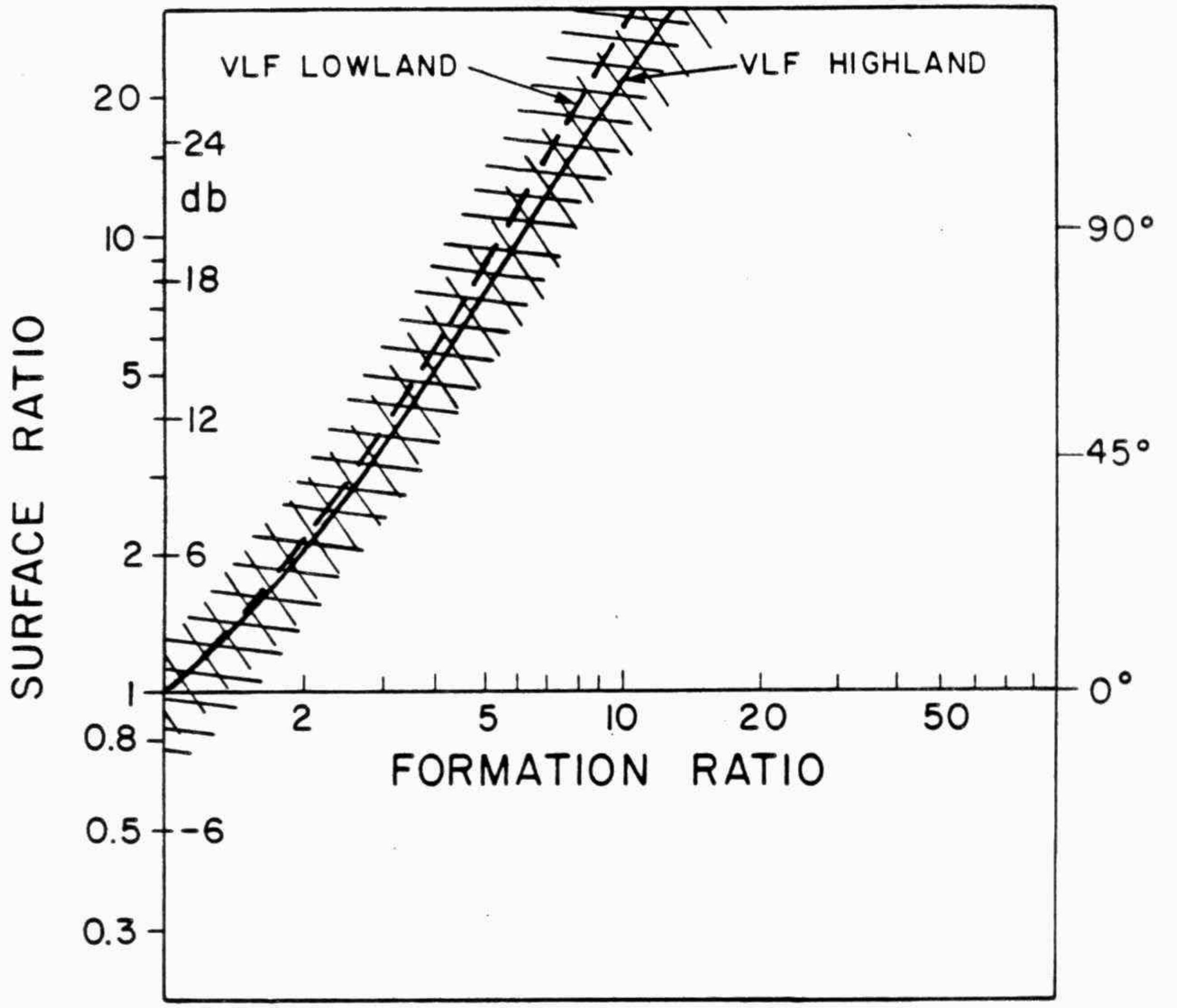


Figure 2.14: EM-16R VLF prediction curves

## 2.8 Predictive Modelling of the resistivity methods

The usefulness of defining the geophysical "detectability" of a subsurface target has been discribed by Roy (1970) and by Verma and Mallick (1979). Greenhouse and Slaine (1983, 1986) have outlined a predictive modelling technique for contamination studies that tries to estimate the effect of contamination at depth on surface readings with a variety of instruments. One dimensional model computations are done for 'standard sections', an average vertical conductivity structure for the site. In the case of the North Bay landfill, where there is such an obvious division into the highland and lowland areas (see section 1.1) we have constructed two standard sections, shown in Figure 2.11. To get an idea of the effects of lateral variability in formation conductivity and layer thickness over the area the standard sections are allowed to vary randomly in these parameters so that instead of a singal response curve one gets a response envelope.

Examples of the resulting curves are shown in Figures 2.12, 2.13, and 2.14. These are bilogarithmic plots of the apparent conductivity ratio ($\sigma app/ \ \sigma appb$) versus the formation conductivity ratio ($\sigma fx/ \ \sigma fb$). The steeper the slope of the curve, the better the instrument will be at detecting formation conductivity changes. The shaded areas denote likely variability in the response of the instruments due to variability of the geological parameters.

Figure 2.12, for example, shows the prediction curves for highland and lowland areas to a Wenner 10 meter array. These show that, due to the highly resistive overburden, this particular array has little resolving power for variations in contamination of the sand aquifer. In fact we never attempted to profile the area with this array; the curves are purely for comparison with the inductive resistivity curves that follow. In Figure 2.13 the curves for the EM-31 are shown, again for the lowland and highland areas. Also shown are the groundwater conductivity data for the wells in the lowland area, which will be discussed in a later section. Concerning the highland curve, it seems paradoxical that an instrument that can penetrate only 4 to 6 metres should respond at all changes in groundwater conductivity at a depth of 12 to 18 metres. We see here an artifact of the normalization process; the reading of the instrument is so low in the background area that the minute contaminant-related changes predicted by the model appear as a large percentage of the background. In fact the instrument is useless, because its reading error at these low conductivities is much larger than the range of response. Greenhouse and Slaine (1986) portray the reading error with their curves, to surmount this difficulty. In the lowland areas the response is strong, and within the reading range.

Figure 2.14 shows the VLF response, and it is also strong. Due to the large penetration of the VLF device in the low conductivty unsaturated zone, the device is almost completely insensitive to the surface topography.

These curves were computed after the survey had been run, so that their importance is more academic than practical. In general they should be constructed before a survey to help in its implementation.

# Chapter III

# RESULTS

## 3.1 Bedrock beneath the site

The EM-16R clearly show a plume-like conductivity anomaly extending southwestward from the North Bay landfill. At the same time, the seismic and gravity data show a bedrock depression occupying roughly the same area as the conductivity high. With the electrical methods it is clearly difficult to separate the effects of the contaminated groundwater and an increase in the depth to bedrock. Both produce an increase in apparent conductivity at the surface.

The zero decibel contour of Figure 2.10 has been chosen on the premise that it represents a thick section of uncontaminated, saturated sand, overlying a very resistive bedrock. This implies that lower apparent conductivities-decibel levels below zero can only be due to a reduced depth to bedrock. On this basis we are reasonably confident that the effects of bedrock and contamination can be crudely separated by VLF and seismic data used together.

We conclude then that contaminated plume is largely coincident with and therefore probably controlled to some extent by the bedrock topography.

## 3.2 A comparison of the geophysical results with borehole conductivity data.

This comparison can be made with two separate sets of data. In Figure 3.1 the 0 and 12 db VLF contours are compared with the chloride concentrations found in the boreholes (indicated on the diagram) downgradient from the site by Hewetson et.al.(1982). Chloride is a good indicator of plume's maximum migration since its mobility is not influenced by chemical processes such as adsorption, precipitation, oxidation or reduction. The chloride background is taken as 50 mg/l, and contours in factor of two increments (100, 200, etc) have been drawn by the author based on the original data. The two VLF contours are background, and a factor of 4 (12 db) above background. they can then be compared with the 50 and 200 mg/l contours respectively.

The comparison of the background contours is fairly good if the density of chloride sampling is considered. The comparison of the 4 times contours is not very good. From a geophysical point of view, there is a tendency to rationalize the overall fit by pointing out that the VLF data set is much more complete, and the choice of a chloride background rather arbitrary. Taking the other side of the fence, the hydrogeologist would probably point out that the chloride data are a direct indication of contamination, whereas the VLF conductivities are averages over a number of parameters, including groundwater conductivity, bedrock depth and overburden stratigraphy. Such arguments are possibly beside the point when the difference in time (more than 3 years) between the two sets of measurements is considered. Groundwater velocities are very high at this site, and temporal changes therefore possible. The most interesting area of disagreement is in the northwest where the VLF data suggest that the plume extends much more in this direction than chloride data show. This deviation is not likely to be produced by the increase in elevation of the surface readings above the cliff, this would decrease rather than increase apparent conductivity. The deviation is based on a fair number of VLF observations, and we therefore suggest it is real and should be investigated by drilling.

The other area for comparison is in the area of the two hydrogeological 'fences', shown in Figure 2.9 and again in Figure 3.2. Here the EM-31 data can be compared with electrical conductivities measured in the 32 drill holes (Moore and Genshi, personal correspondence, 1985). Their measurements of electrical conductivity, measured in multilevel piezometers placed every 2 metre were averaged by adding the values up to 5 metres depth and divide them to whatever number of reading we obtained to that depth.

The comparison is complicated here by the fact that the EM-31 zero db contour level lies well outside the area of borehole measurements, and is therefore influenced by the main plume and (to the southeast) by the rapid shallowing of the bedrock. The background conductivity for the borehole data has been taken as 50 mS/M, the lowest value encountered in the boreholes. A comparison of Figures 2.10 and 3.2 clearly reveals the same general trend in both data sets, and a surprisingly good quantitative agreement in the conductivity range as well. The penetration of the EM-31 is much less than the assumed 4 metres under these highly conductive conditions, yet the peak plume concentrations were often measured below these depths. To some degree, then, the good agreement is serendipity; still, the value of geophysics as a reconnaissance tool is evident. It is unfortunate that the geophysical survey was not done before the fences were installed, as a better placement might have been possible.

## 3.3 A comparison of the EM-31 and the groundwater conductivity data using the prediction curves.

Figure 2.13 allows us to look at the EM-31 comparison of the last section in another light. The same average specific conductivities are plotted against the apparent conductivities for that well as taken from the contour map, but on the prediction curve axis. The well data should be compared with the "lowland" model curve. The comparison is not flattering, but there are some general points of agreement. The trend of the well data is definitely upward from left to right. Until formation ratios of 10, the trend of model and data is good. Beyond 10, however, there appears to be a breakdown in the relationship. The reason for this discrepancy probably lies in the uneven distribution of the contamination in the section. The model assumes a uniformly contaminated sand. The prediction curves are therefore predicated on high conductivities being present at the very top of the section, and hence detectable by the EM-31.

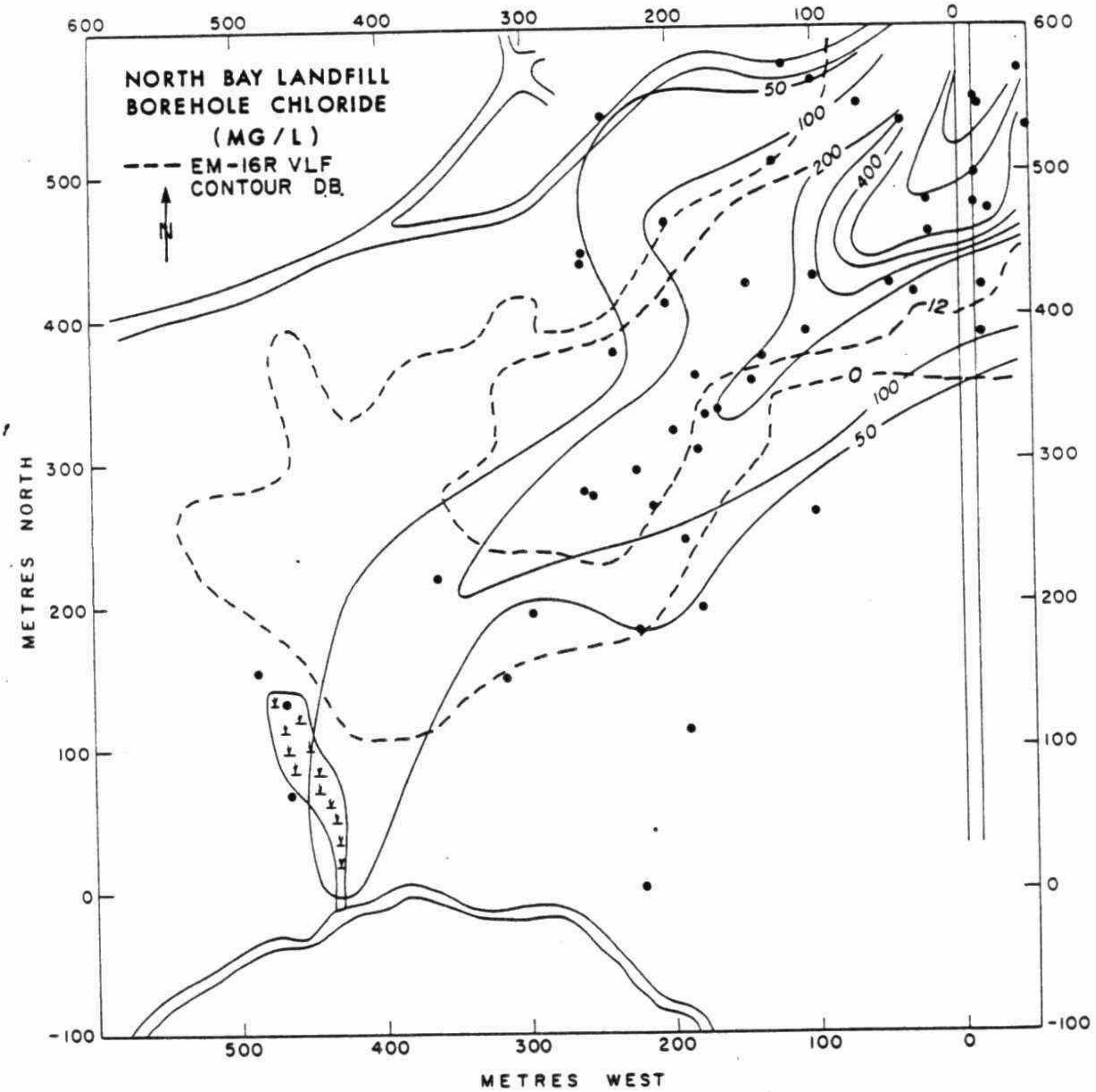


Figure 3.1: Chloride concentration contour map for the survey area compared to VLF data.

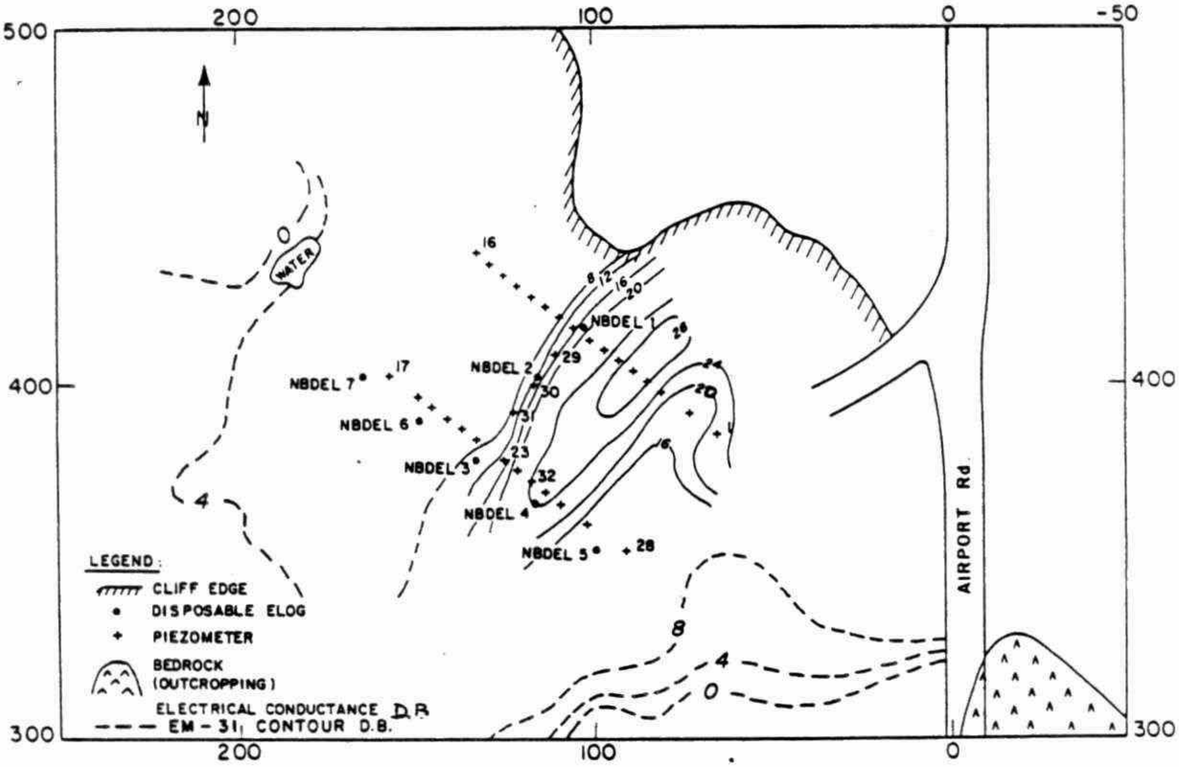


Figure 3.2: Average specific conductivity of water samples in the area of 300-500 m North, 0-200 m west.

# Chapter IV

# CONCLUSIONS AND RECOMMENDATIONS

## 4.1 Conclusions

The geophysical program described in this report has mapped the contaminant plume at the North Bay site using EM resistivity techniques, and also mapped the bedrock topography beneath the plume using seismic and gravity data augmented by drilling results from the hydrogeological studies at this site. The geophysical program has also attempted to evaluate the quantitative use of the geophysical data as a means of obtaining contamination levels as well as location.

The electromagnetic techniques are useful and reliable means of detecting and monitoring the contaminant plume at the North Bay site. The use of a zero decibel contour appears to allow the separation of bedrock topography and contamination to some degree, but the EM methods need the support of gravity and seismic data to properly achieve this separation. The comparisons of EM and groundwater data show that the correlation between the two data sets is qualitatively good. The attempt to use simple one dimensional models to predict average contamination levels was not very successful, due to the complex distribution of contamination in the vertical section. The EM methods remain, then, a good reconnaissance grade survey technique for contaminant plumes.

The seismic refraction data were generally of good quality and they have been interpreted in terms of bedrock depth. The gravity data provide a general confirmation of the seismic results but more coverage should have been obtained.

The combination seismic and EM data show, beyond much doubt, that the contaminant plume overlies a bedrock valley. The implication is clearly that the plumes movement is influenced to some degree by that bedrock topography.

## 4.2 Recommendations

The geological methodology described herein outlines a contaminant hydrogeological reconnaissance technique. The method would be most useful as an adjunct to groundwater monitoring program. It is not meant to replace the hydrogeological mapping of a contaminant plume via groudwater chemical analysis, but rather serve as a guide on where- or where not-to concentrate hydrogeological studies.

In order to fully understand the behavior of the bedrock surface, especially west of the discharge area and northwest part of the grid, the following recommendations are made:

(i) Further seismic lines should be done, in order to determine the southwest extent of the bedrock surface beyond the discharge area, especially in the region of 120 North, 400 West.

(ii) More resistivity soundings should be done north and northwest of the grid in order to provide depths of the site's subsurface.

(iii) Short preliminary surveys, combined with predictive modelling, should be used routinely to evaluate the role of geophysics prior to the main study. Existing well log records can sometimes provide information on the site's subsurface.

(iv) Even with the limitations inherent to surface geophysics, proper definition of its role in contaminant monitoring and a standardized display should increase its use by the hydrogeological community. The benefits of this are both increased speed and reduced cost of the task of monitoring or mapping contaminant groundwater.

(V) More gravity readings should be made in order to determine the north and southwest extent of the bedrock surface.

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# Appendix A

# RESISTIVITY RAW DATA

```
NORTH   BAY      SNDG #1   240N 56W AUG 21  EW

AB/2      MN/2    DV           I       K        RHO APP
 (M)       (M)   (MV)        (MA)             (OHM-M)
--------------------------------------------------------
    1.50      0.50  10000.00     30.00     6.28    2094.39
    2.00      0.50   5240.00     30.00    11.78    2057.74
    2.50      0.50   3280.00     30.00    18.85    2060.88
    3.00      0.50   2320.00     30.00    27.49    2125.81
    4.00      0.50   1900.00     40.00    49.48    2350.30
    5.00      0.50   1000.00     30.00    77.75    2591.81
    6.00      0.50    774.00     30.00   112.31    2897.65
    8.00      0.50    632.00     40.00   200.28    3164.37
   10.00      0.50    350.00     30.00   313.37    3656.03
   12.50      0.50    321.00     40.00   490.09    3932.96
   15.00      0.50    224.00     40.00   706.07    3954.01
   20.00      0.50    130.00     40.00  1255.85    4081.51
   25.00      0.50     18.80     10.00  1962.71    3689.89
   30.00      0.50                      2826.65        ERR
   40.00      0.50                      5025.76        ERR
   50.00      0.50
   60.00      0.50
```

```
NORTH   BAY      SNDG #2   240N222W AUG 21

AB/2      MN/2    DV           I       K        RHO APP
(M)       (M)     (MV)       (MA)             (OHM-M)
--------------------------------------------------------
    1.50      0.50  28600.00      5.00     6.28   35939.73
    2.00      0.50  19400.00      5.50    11.78   41554.67
    2.50      0.50   6400.00      3.50    18.85   34467.73
    3.00      0.50   7160.00      6.10    27.49   32265.67
    4.00      0.50   2680.00      5.00    49.48   26521.30
    5.00      0.50   1210.00      5.00    77.75   18816.55
    6.00      0.50    310.00      3.00   112.31   11605.56
    8.00      0.50    540.00     11.50   200.28    9404.28
   10.00      0.50    250.00     13.00   313.37    6026.42
   12.50      0.50    174.00     20.00   490.09    4263.77
   15.00      0.50     62.00     19.50   706.07    2244.95
   20.00      0.50     20.00     22.50  1255.85    1116.31
   25.00      0.50      4.50     16.00  1962.71     552.01
   30.00      0.50      2.00     19.50  2826.65     289.91
   30.00      5.00     18.50     19.80   274.89     256.84
   40.00      5.00     13.60     22.60   494.80     297.76
   50.00      5.00     17.00     35.00   777.54     377.66
   60.00      5.00      8.50     19.50  1123.12     489.56
```

```
NORTH   BAY     SNDG #3   430N 230 AUG 27 NE/SW

AB/2     MN/2   DV             I        K        RHO APP
(M)     (M)     (MV)       (MA)               (OHM-M)
-------------------------------------------------------------
    1.50     0.50   2400.00    20.00     6.28     753.98
    2.00     0.50   1410.00    30.00    11.78     553.71
    2.50     0.50    810.00    30.00    18.85     508.94
    3.00     0.50    520.00    30.00    27.49     476.47
    4.00     0.50    290.00    30.00    49.48     478.31
    5.00     0.50    190.00    30.00    77.75     492.44
    6.00     0.50    140.00    30.00   112.31     524.12
    8.00     0.50     80.00    30.00   200.28     534.07
   10.00     1.00    110.00    30.00   155.51     570.20
   12.50     1.00     70.00    30.00   243.87     569.02
   15.00     2.00    140.00    30.00   173.57     810.01
   20.00     2.00     90.00    30.00   311.02     933.05
   25.00     2.00     70.00    30.00   487.73    1138.04
   30.00     5.00    170.00    40.00   274.89    1168.28
   40.00     5.00    120.00    40.00   494.80    1484.40
   50.00     5.00     90.00    40.00   777.54    1749.47
   60.00     0.50
```

# Appendix B

# GRAVITY RAW DATA

```
TITLE NORTHBAY SURVEY 1984: 1 GRAVITY CONTOUR, MGALS
IDXY 500,11,3,1,2,3,0,0,0,,'(2F10.1,F10.1 )'
POST 2,0,.05,.05,0
DEVICE 6,'GREENHOUSE',1200.,33.5
BOX 25,4,25,4,0,0,-100,1,.25
BXEX 0,650,-100,600
SIZC 0,50.9554,50.9554
PERFORM
GRID 1,20,20,0,0,0,0
EXTREMES 0,650,-100,600
CINT 0,-60,10,12,,,0,,4
CONTOUR
OVERLAY
PERFORM
STOP
```

Northbay Gravity Survey Aug. 1984 DENSITY: 1.80

| Northing (m) | Westing (m) | Elevation | Gravity Reading | Drift Correction | Gravity in Mgals | Latitude Correction |
|---|---|---|---|---|---|---|
| 120.00 | 0.00 | 337.37 | 465.10 | 1.10 | 47.03 | -0.10 |
| 120.00 | 30.00 | 337.17 | 465.70 | 1.20 | 47.10 | -0.10 |
| 120.00 | 60.00 | 337.72 | 466.20 | 1.30 | 47.16 | -0.10 |
| 120.00 | 90.00 | 336.33 | 467.60 | 1.40 | 47.31 | -0.10 |
| 120.00 | 120.00 | 334.44 | 469.50 | 2.10 | 47.58 | -0.10 |
| 120.00 | 240.00 | 346.24 | 439.61 | 1.50 | 44.50 | -0.10 |
| 120.00 | 270.00 | 346.28 | 440.10 | 1.40 | 44.54 | -0.10 |
| 120.00 | 300.00 | 346.04 | 440.30 | 1.30 | 44.55 | -0.10 |
| 120.00 | 330.00 | 346.04 | 439.00 | 1.20 | 44.41 | -0.10 |
| 120.00 | 360.00 | 342.58 | 445.90 | 1.20 | 45.10 | -0.10 |
| 120.00 | 390.00 | 331.99 | 471.10 | 1.00 | 47.63 | -0.10 |
| 120.00 | 420.00 | 331.26 | 473.60 | 0.90 | 47.87 | -0.10 |
| 120.00 | 480.00 | 336.22 | 463.30 | 0.60 | 46.80 | -0.10 |
| 180.00 | 0.00 | 338.38 | 462.30 | 1.05 | 46.74 | -0.05 |
| 180.00 | 30.00 | 338.29 | 462.90 | 1.10 | 46.81 | -0.05 |
| 180.00 | 60.00 | 338.05 | 463.90 | 1.10 | 46.91 | -0.05 |
| 180.00 | 90.00 | 337.18 | 465.90 | 1.10 | 47.11 | -0.05 |
| 180.00 | 120.00 | 335.95 | 468.90 | 0.80 | 47.38 | -0.05 |
| 180.00 | 150.00 | 335.96 | 467.90 | 0.70 | 47.27 | -0.05 |
| 180.00 | 180.00 | 334.76 | 469.00 | 0.67 | 47.39 | -0.05 |
| 180.00 | 210.00 | 335.60 | 467.20 | 0.60 | 47.19 | -0.05 |
| 180.00 | 240.00 | 344.66 | 444.50 | 1.55 | 45.00 | -0.05 |
| 180.00 | 244.00 | 345.00 | 441.70 | 1.55 | 44.72 | -0.05 |
| 180.00 | 270.00 | 347.19 | 438.30 | 1.55 | 44.37 | -0.05 |
| 180.00 | 300.00 | 346.27 | 440.50 | 1.55 | 44.59 | -0.05 |
| 180.00 | 330.00 | 346.32 | 437.95 | 1.55 | 44.34 | -0.05 |
| 180.00 | 360.00 | 346.25 | 441.00 | 1.55 | 44.64 | -0.05 |
| 180.00 | 390.00 | 346.31 | 439.35 | 1.55 | 44.48 | -0.05 |
| 180.00 | 420.00 | 343.86 | 460.60 | -13.60 | 45.09 | -0.05 |
| 240.00 | 0.00 | 337.98 | 461.70 | 0.00 | 46.58 | 0.00 |
| 240.00 | 30.00 | 338.42 | 463.20 | 0.15 | 46.74 | 0.00 |
| 240.00 | 60.00 | 336.90 | 468.10 | 0.20 | 47.24 | 0.00 |
| 240.00 | 120.00 | 337.31 | 464.70 | 0.29 | 46.91 | 0.00 |
| 240.00 | 150.00 | 337.35 | 464.25 | 0.32 | 46.87 | 0.00 |
| 240.00 | 180.00 | 336.50 | 466.40 | 0.40 | 47.03 | 0.00 |
| 240.00 | 210.00 | 336.80 | 465.55 | 0.50 | 47.02 | 0.00 |
| 240.00 | 240.00 | 340.00 | 452.25 | 1.55 | 45.78 | 0.00 |
| 240.00 | 270.00 | 346.55 | 439.50 | 1.55 | 44.49 | 0.00 |
| 240.00 | 300.00 | 345.62 | 443.20 | 1.55 | 44.87 | 0.00 |
| 240.00 | 330.00 | 345.92 | 441.80 | 1.55 | 44.73 | 0.00 |
| 240.00 | 360.00 | 346.29 | 441.00 | 1.55 | 44.64 | 0.00 |
| 240.00 | 390.00 | 346.30 | 440.75 | 1.55 | 44.62 | 0.00 |
| 240.00 | 420.00 | 346.32 | 440.50 | 1.55 | 44.59 | 0.00 |
| 300.00 | 0.00 | 339.92 | 461.00 | 0.05 | 46.51 | 0.05 |
| 300.00 | 30.00 | 338.28 | 465.70 | 0.05 | 46.98 | 0.05 |
| 300.00 | 60.00 | 337.12 | 468.40 | 0.05 | 47.26 | 0.05 |
| 300.00 | 90.00 | 336.91 | 469.70 | 0.05 | 47.39 | 0.05 |
| 300.00 | 180.00 | 336.82 | 465.10 | 0.05 | 46.92 | 0.05 |
| 300.00 | 210.00 | 337.76 | 463.30 | 0.05 | 46.74 | 0.05 |
| 300.00 | 300.00 | 346.07 | 442.00 | 2.87 | 44.88 | 0.05 |
| 300.00 | 330.00 | 346.25 | 442.30 | 2.95 | 44.92 | 0.05 |
| 300.00 | 360.00 | 346.09 | 441.80 | 3.15 | 44.89 | 0.05 |

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 Bouguer   Final Gravity       G-GBAR  H-HBAR  PRODUCT    H*H
Correction    in Mgals

     -0.16        0.40           0.22    -3.27     -0.73     10.68
     -0.21        0.42           0.24    -3.47     -0.84     12.03
     -0.07        0.62           0.44    -2.92     -1.29      8.52
     -0.42        0.41           0.24    -4.31     -1.04     18.56
     -0.90        0.20           0.02    -6.20     -0.14     38.42
      2.10        0.12          -0.05     5.60     -0.30     31.38
      2.11        0.17          -0.00     5.64     -0.03     31.83
      2.05        0.12          -0.06     5.40     -0.30     29.16
      2.05       -0.02          -0.20     5.41     -1.06     29.23
      1.17       -0.21          -0.38     1.94     -0.74      3.77
     -1.52       -0.38          -0.55    -8.65      4.75     74.80
     -1.71       -0.32          -0.49    -9.38      4.62     87.96
     -0.45       -0.13          -0.30    -4.42      1.33     19.52
      0.10        0.32           0.14    -2.26     -0.32      5.10
      0.08        0.36           0.19    -2.35     -0.44      5.52
      0.02        0.40           0.23    -2.59     -0.58      6.70
     -0.20        0.38           0.21    -3.46     -0.71     11.96
     -0.52        0.34           0.17    -4.69     -0.78     21.98
     -0.51        0.23           0.06    -4.68     -0.27     21.89
     -0.82        0.03          -0.14    -5.88      0.82     34.56
     -0.60        0.06          -0.11    -5.04      0.58     25.39
      1.70        0.17          -0.01     4.02     -0.02     16.17
      1.78       -0.03          -0.20     4.36     -0.88     19.02
      2.34        0.18           0.01     6.55      0.07     42.92
      2.11        0.17          -0.00     5.63     -0.00     31.71
      2.12       -0.07          -0.25     5.68     -1.39     32.23
      2.10        0.22           0.04     5.61      0.25     31.49
      2.12        0.07          -0.11     5.67     -0.60     32.17
      1.49        0.06          -0.11     3.22     -0.37     10.38
      0.00        0.00          -0.17    -2.66      0.46      7.07
      0.11        0.28           0.10    -2.22     -0.23      4.92
     -0.27        0.39           0.22    -3.74     -0.81     13.99
     -0.17        0.16          -0.01    -3.33      0.04     11.08
     -0.16        0.13          -0.04    -3.29      0.14     10.81
     -0.38        0.14          -0.04    -4.14      0.14     17.13
     -0.30        0.14          -0.03    -3.84      0.13     14.73
      0.51       -0.28          -0.46    -0.64      0.29      0.41
      2.18        0.09          -0.08     5.91     -0.47     34.95
      1.94        0.23           0.06     4.98      0.29     24.84
      2.02        0.17          -0.01     5.28     -0.03     27.92
      2.11        0.18           0.01     5.65      0.04     31.94
      2.11        0.16          -0.02     5.66     -0.10     32.02
      2.12        0.14          -0.04     5.69     -0.20     32.38
      0.49        0.38           0.21    -0.72     -0.15      0.52
      0.08        0.44           0.26    -2.36     -0.62      5.56
     -0.22        0.41           0.24    -3.52     -0.85     12.39
     -0.27        0.49           0.32    -3.73     -1.19     13.90
     -0.29        0.00          -0.17    -3.82      0.64     14.58
     -0.06        0.06          -0.11    -2.88      0.32      8.29
      2.06        0.31           0.14     5.43      0.74     29.52
      2.10        0.39           0.22     5.61      1.23     31.49
      2.06        0.32           0.15     5.45      0.81     29.72
                  0.17                               0.23   1155.17

                                PARASNIS:          1.304649GMS/CC
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# Appendix C

# VLF AND EM-31 CONDUCTIVITY RAW DATA

```
      TITLE NORTHBAY SURVEY 1984/85:  VLF PHASE CONTOURS, 500
OM BACK
      IDXY 500,11,3,1,,3,0,0,0,,'(2F10.1,10X,2F10.1)'
      POST 2,0,.05,.05,0
      DEVICE 6,'GREENHOUSE',1200.,33.5
      BOX 25,4,25,4,0,0,-100,1,.25
      BXEX 0,650,-100,600
      SIZC 0,50.9554,50.9554
      PERFORM
      GRID 1,15,15,0,0,0,0
      EXTREMES 0,650,-100,600
      CINT 0,0, 10,13,,,0,,4
      CONTOUR
      OVERLAY
      PERFORM
      STOP
```

| Northing(m) | Westing(m) | VLF(mS/m) | Phase | mS/m | |
|---|---|---|---|---|---|
| 600.00 | 450.00 | 63.00 | 21.00 | 15.87 | 17.99 |
| 570.00 | 450.00 | 10.00 | 56.00 | 100.00 | 33.98 |
| 540.00 | 450.00 | 29.00 | 44.00 | 34.48 | 24.73 |
| 540.00 | 480.00 | 75.00 | 56.00 | 13.33 | 16.48 |
| 570.00 | 390.00 | 145.00 | 31.00 | 6.90 | 10.75 |
| 510.00 | 510.00 | 320.00 | 55.00 | 3.13 | 3.88 |
| 540.00 | 510.00 | 130.00 | 50.00 | 7.69 | 11.70 |
| 480.00 | 520.00 | 1200.00 | 43.00 | 0.83 | -7.60 |
| 450.00 | 520.00 | 1800.00 | 30.00 | 0.56 | -11.13 |
| 420.00 | 510.00 | 2800.00 | 18.00 | 0.36 | -14.96 |
| 420.00 | 480.00 | 1300.00 | 33.00 | 0.77 | -8.30 |
| 210.00 | 510.00 | 1550.00 | 51.00 | 0.65 | -9.83 |
| 210.00 | 410.00 | 1400.00 | 46.00 | 0.71 | -8.94 |
| 390.00 | 60.00 | 6500.00 | 30.00 | 0.15 | -22.28 |
| 360.00 | 60.00 | 2400.00 | 45.00 | 0.42 | -13.62 |
| 330.00 | 60.00 | 3100.00 | 38.00 | 0.32 | -15.85 |
| 300.00 | 60.00 | 3000.00 | 42.00 | 0.33 | -15.56 |
| 270.00 | 60.00 | 1200.00 | 45.00 | 0.83 | -7.60 |
| 240.00 | 60.00 | 1200.00 | 31.00 | 0.83 | -7.60 |
| 210.00 | 60.00 | 1900.00 | 45.00 | 0.53 | -11.60 |
| 480.00 | 60.00 | 3200.00 | 30.00 | 0.31 | -16.12 |
| 450.00 | 60.00 | 5100.00 | 33.00 | 0.20 | -20.17 |
| 420.00 | 60.00 | 8500.00 | 24.00 | 0.12 | -24.61 |
| 390.00 | 90.00 | 3600.00 | 33.20 | 0.28 | -17.15 |
| 360.00 | 90.00 | 2530.00 | 38.10 | 0.40 | -14.08 |
| 330.00 | 90.00 | 2500.00 | 39.10 | 0.40 | -13.98 |
| 300.00 | 90.00 | 1500.00 | 38.50 | 0.67 | -9.54 |
| 270.00 | 90.00 | 1100.00 | 48.00 | 0.91 | -6.85 |
| 240.00 | 90.00 | 810.00 | 43.60 | 1.23 | -4.19 |
| 225.00 | 90.00 | 1380.00 | 40.50 | 0.72 | -8.82 |
| 330.00 | 120.00 | 850.00 | 39.00 | 1.18 | -4.61 |
| 300.00 | 120.00 | 1100.00 | 50.00 | 0.91 | -6.85 |
| 270.00 | 120.00 | 800.00 | 48.00 | 1.25 | -4.08 |
| 255.00 | 120.00 | 375.00 | 57.00 | 2.67 | 2.50 |
| 240.00 | 120.00 | 230.00 | 50.00 | 4.35 | 6.74 |
| 225.00 | 120.00 | 520.00 | 44.00 | 1.92 | -0.34 |
| 210.00 | 120.00 | 300.00 | 38.00 | 3.33 | 4.44 |
| 195.00 | 120.00 | 300.00 | 45.00 | 3.33 | 4.44 |
| 180.00 | 120.00 | 500.00 | 40.00 | 2.00 | 0.00 |
| 165.00 | 120.00 | 800.00 | 25.00 | 1.25 | -4.08 |
| 150.00 | 120.00 | 850.00 | 30.00 | 1.18 | -4.61 |
| 135.00 | 120.00 | 1200.00 | 40.00 | 0.83 | -7.60 |
| 120.00 | 120.00 | 1100.00 | 48.00 | 0.91 | -6.85 |
| 105.00 | 120.00 | 650.00 | 37.00 | 1.54 | -2.28 |
| 90.00 | 120.00 | 2100.00 | 38.00 | 0.48 | -12.46 |
| 60.00 | 120.00 | 3500.00 | 32.00 | 0.29 | -16.90 |
| 30.00 | 120.00 | 3500.00 | 38.00 | 0.29 | -16.90 |
| 345.00 | 120.00 | 2500.00 | 41.00 | 0.40 | -13.98 |
| 360.00 | 120.00 | 1500.00 | 35.00 | 0.67 | -9.54 |
| 375.00 | 120.00 | 2200.00 | 38.00 | 0.45 | -12.87 |
| 390.00 | 120.00 | 2400.00 | 35.00 | 0.42 | -13.62 |
| 405.00 | 120.00 | 1100.00 | 37.00 | 0.91 | -6.85 |

| | | | | | |
|---|---|---|---|---|---|
| 360.00 | 150.00 | 1600.00 | 45.00 | 0.63 | -10.10 |
| 330.00 | 150.00 | 800.00 | 51.80 | 1.25 | -4.08 |
| 300.00 | 150.00 | 502.00 | 52.00 | 1.99 | -0.03 |
| 270.00 | 150.00 | 400.00 | 47.00 | 2.50 | 1.94 |
| 240.00 | 150.00 | 300.00 | 59.00 | 3.33 | 4.44 |
| 210.00 | 150.00 | 200.00 | 68.00 | 5.00 | 7.96 |
| 190.00 | 150.00 | 200.00 | 56.00 | 5.00 | 7.96 |
| 180.00 | 180.00 | 450.00 | 43.00 | 2.22 | 0.92 |
| 195.00 | 180.00 | 350.00 | 52.00 | 2.86 | 3.10 |
| 210.00 | 180.00 | 160.00 | 42.00 | 6.25 | 9.90 |
| 225.00 | 180.00 | 350.00 | 49.00 | 2.86 | 3.10 |
| 240.00 | 180.00 | 230.00 | 55.00 | 4.35 | 6.74 |
| 255.00 | 180.00 | 260.00 | 55.00 | 3.85 | 5.68 |
| 270.00 | 180.00 | 400.00 | 55.00 | 2.50 | 1.94 |
| 285.00 | 180.00 | 210.00 | 52.00 | 4.76 | 7.54 |
| 300.00 | 180.00 | 230.00 | 45.00 | 4.35 | 6.74 |
| 315.00 | 180.00 | 1100.00 | 44.00 | 0.91 | -6.85 |
| 330.00 | 180.00 | 70.00 | 63.00 | 14.29 | 17.08 |
| 345.00 | 180.00 | 210.00 | 52.00 | 4.76 | 7.54 |
| 360.00 | 180.00 | 350.00 | 50.00 | 2.86 | 3.10 |
| 315.00 | 120.00 | 1400.00 | 46.00 | 0.71 | -8.94 |
| 420.00 | 120.00 | 4500.00 | 32.00 | 0.22 | -19.08 |
| 450.00 | 120.00 | 5000.00 | 29.00 | 0.20 | -20.00 |
| 480.00 | 120.00 | 5800.00 | 31.00 | 0.17 | -21.29 |
| 510.00 | 120.00 | 10000.00 | 28.00 | 0.10 | -26.02 |
| 540.00 | 120.00 | 4000.00 | 35.00 | 0.25 | -18.06 |
| 570.00 | 120.00 | 13000.00 | 35.00 | 0.08 | -28.30 |
| 285.00 | 120.00 | 950.00 | 43.00 | 1.05 | -5.58 |
| 300.00 | 120.00 | 1150.00 | 48.00 | 0.87 | -7.23 |
| 315.00 | 120.00 | 1400.00 | 46.00 | 0.71 | -8.94 |
| 180.00 | 210.00 | 405.00 | 64.00 | 2.47 | 1.83 |
| 210.00 | 210.00 | 280.00 | 64.00 | 3.57 | 5.04 |
| 240.00 | 210.00 | 132.00 | 67.50 | 7.58 | 11.57 |
| 270.00 | 210.00 | 203.00 | 68.20 | 4.93 | 7.83 |
| 300.00 | 210.00 | 132.00 | 61.50 | 7.58 | 11.57 |
| 330.00 | 210.00 | 600.00 | 58.00 | 1.67 | -1.58 |
| 450.00 | 210.00 | 3500.00 | 30.00 | 0.29 | -16.90 |
| 435.00 | 210.00 | 2800.00 | 26.00 | 0.36 | -14.96 |
| 420.00 | 210.00 | 2300.00 | 26.00 | 0.43 | -13.26 |
| 405.00 | 210.00 | 160.00 | 30.00 | 6.25 | 9.90 |
| 390.00 | 210.00 | 120.00 | 27.00 | 8.33 | 12.40 |
| 375.00 | 210.00 | 110.00 | 28.00 | 9.09 | 13.15 |
| 540.00 | 180.00 | 4500.00 | 32.00 | 0.22 | -19.08 |
| 525.00 | 180.00 | 4000.00 | 32.00 | 0.25 | -18.06 |
| 510.00 | 180.00 | 3000.00 | 30.00 | 0.33 | -15.56 |
| 495.00 | 180.00 | 3500.00 | 30.00 | 0.29 | -16.90 |
| 480.00 | 180.00 | 5000.00 | 28.00 | 0.20 | -20.00 |
| 465.00 | 180.00 | 5000.00 | 31.00 | 0.20 | -20.00 |
| 450.00 | 180.00 | 4000.00 | 30.00 | 0.25 | -18.06 |
| 435.00 | 180.00 | 5000.00 | 30.00 | 0.20 | -20.00 |
| 420.00 | 180.00 | 6500.00 | 29.00 | 0.15 | -22.28 |
| 405.00 | 180.00 | 850.00 | 31.00 | 1.18 | -4.61 |
| 390.00 | 180.00 | 220.00 | 30.00 | 4.55 | 7.13 |
| 375.00 | 180.00 | 500.00 | 32.00 | 2.00 | 0.00 |

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365.00    240.00      85.00    10.00    11.76    15.39
330.00    240.00      34.00    45.00    29.41    23.35
315.00    240.00     190.00    56.00     5.26     8.40
300.00    240.00      80.00    48.00    12.50    15.92
285.00    240.00     110.00    51.00     9.09    13.15
270.00    240.00     120.00    53.00     8.33    12.40
255.00    240.00     160.00    53.00     6.25     9.90
240.00    240.00     180.00    57.00     5.56     8.87
225.00    240.00     350.00    40.00     2.86     3.10
210.00    240.00     600.00    47.00     1.67    -1.58
195.00    240.00     400.00    45.00     2.50     1.94
180.00    240.00     500.00    43.00     2.00     0.00
165.00    240.00     435.00    40.00     2.30     1.21
345.00    240.00      10.00    18.00   100.00    33.98
330.00    240.00      21.00    40.00    47.62    27.53
375.00    240.00     110.00    32.00     9.09    13.15
405.00    240.00     180.00    13.00     5.56     8.87
420.00    240.00     320.00    16.00     3.13     3.68
435.00    240.00     500.00    21.00     2.00     0.00
450.00    240.00    1800.00    28.00     0.56   -11.13
465.00    240.00    1700.00    31.00     0.59   -10.63
480.00    240.00    1600.00    32.00     0.63   -10.10
495.00    240.00    1800.00    36.00     0.56   -11.13
525.00    240.00   11000.00    30.00     0.09   -26.85
540.00    240.00    6000.00    34.00     0.17   -21.58
555.00    240.00    7500.00    32.00     0.13   -23.52
570.00    240.00    5000.00    31.00     0.20   -20.00
420.00    270.00     110.00    58.00     9.09    13.15
390.00    270.00      70.00    40.00    14.29    17.08
360.00    270.00      83.00    52.50    12.05    15.60
300.00    270.00      85.00    70.00    11.63    15.29
270.00    270.00      70.00    60.80    14.29    17.08
240.00    270.00     196.00    62.00     5.10     8.13
210.00    270.00     290.00    58.00     3.45     4.73
180.00    270.00     503.00    51.00     1.99    -0.05
620.00    300.00    6000.00    60.00     0.17   -21.58
570.00    300.00    2300.00    43.00     0.43   -13.26
555.00    300.00    2100.00    44.00     0.48   -12.46
540.00    300.00    3000.00    40.00     0.33   -15.56
510.00    300.00    2400.00    32.00     0.42   -13.62
495.00    300.00     800.00    35.00     1.25    -4.08
480.00    300.00     400.00    29.00     2.50     1.94
465.00    300.00     500.00    18.00     2.00     0.00
420.00    300.00     120.00    28.00     8.33    12.40
405.00    300.00      90.00    27.00    11.11    14.89
390.00    300.00      70.00    20.00    14.29    17.08
375.00    300.00      90.00    21.00    11.11    14.89
360.00    300.00      95.00    38.00    10.53    14.42
345.00    300.00     110.00    35.00     9.09    13.15
330.00    300.00      90.00    48.00    11.11    14.89
300.00    300.00     100.00    62.00    10.00    13.98
385.00    300.00     110.00    53.00     9.09    13.15
270.00    300.00     350.00    58.00     2.86     3.10
255.00    300.00     250.00    53.00     4.00     6.02
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| | | | | | |
|---|---|---|---|---|---|
| 240.00 | 300.00 | 220.00 | 48.00 | 4.55 | 7.13 |
| 210.00 | 300.00 | 240.00 | 37.00 | 4.17 | 6.38 |
| 180.00 | 300.00 | 250.00 | 30.00 | 4.00 | 6.02 |
| 120.00 | 300.00 | 1300.00 | 36.00 | 0.77 | -8.30 |
| 330.00 | 330.00 | 41.00 | 68.00 | 24.39 | 21.72 |
| 300.00 | 330.00 | 60.00 | 78.00 | 16.67 | 18.42 |
| 270.00 | 330.00 | 220.00 | 54.80 | 4.55 | 7.13 |
| 240.00 | 330.00 | 320.00 | 44.00 | 3.13 | 3.88 |
| 210.00 | 330.00 | 407.00 | 39.20 | 2.46 | 1.79 |
| 180.00 | 330.00 | 900.00 | 35.00 | 1.11 | -5.11 |
| 610.00 | 360.00 | 170.00 | 38.00 | 5.88 | 9.37 |
| 360.00 | 360.00 | 70.00 | 34.00 | 14.29 | 17.08 |
| 600.00 | 390.00 | 110.00 | 28.00 | 9.09 | 13.15 |
| 510.00 | 390.00 | 90.00 | 18.00 | 11.11 | 14.89 |
| 450.00 | 390.00 | 80.00 | 33.00 | 12.50 | 15.92 |
| 420.00 | 390.00 | 32.00 | 24.00 | 31.25 | 23.88 |
| 390.00 | 390.00 | 140.00 | 29.00 | 7.14 | 11.06 |
| 360.00 | 390.00 | 800.00 | 36.00 | 1.25 | -4.08 |
| 330.00 | 390.00 | 1100.00 | 38.00 | 0.91 | -6.85 |
| 630.00 | 390.00 | 120.00 | 24.00 | 8.33 | 12.40 |
| 660.00 | 390.00 | 200.00 | 24.00 | 5.00 | 7.96 |
| 300.00 | 390.00 | 300.00 | 30.00 | 3.33 | 4.44 |
| 270.00 | 390.00 | 700.00 | 32.00 | 1.43 | -2.92 |
| 345.00 | 390.00 | 1000.00 | 33.00 | 1.00 | -6.02 |
| 405.00 | 390.00 | 100.00 | 28.00 | 10.00 | 13.98 |
| 435.00 | 390.00 | 60.00 | 10.00 | 16.67 | 18.42 |
| 570.00 | 390.00 | 160.00 | 20.00 | 6.25 | 9.90 |
| 555.00 | 390.00 | 80.00 | 26.00 | 12.50 | 15.92 |
| 540.00 | 390.00 | 98.00 | 18.00 | 10.20 | 14.15 |
| 525.00 | 390.00 | 130.00 | 16.00 | 7.69 | 11.70 |
| 495.00 | 390.00 | 80.00 | 19.00 | 12.50 | 15.92 |
| 480.00 | 390.00 | 45.00 | 23.00 | 22.22 | 20.92 |
| 465.00 | 390.00 | 50.00 | 25.00 | 20.00 | 20.00 |
| 495.00 | 420.00 | 29.00 | 19.00 | 34.48 | 24.73 |
| 525.00 | 420.00 | 50.00 | 12.00 | 20.00 | 20.00 |
| 555.00 | 420.00 | 50.00 | 11.00 | 20.00 | 20.00 |
| 270.00 | 420.00 | 1200.00 | 45.00 | 0.83 | -7.60 |
| 450.00 | 420.00 | 30.00 | 34.00 | 33.33 | 24.44 |
| 420.00 | 420.00 | 200.00 | 34.00 | 5.00 | 7.96 |
| 390.00 | 420.00 | 400.00 | 40.00 | 2.50 | 1.94 |
| 360.00 | 420.00 | 1500.00 | 38.00 | 0.67 | -9.54 |
| 450.00 | 450.00 | 70.00 | 30.00 | 14.29 | 17.08 |
| 420.00 | 450.00 | 230.00 | 30.00 | 4.35 | 6.74 |
| 390.00 | 450.00 | 900.00 | 38.00 | 1.11 | -5.11 |
| 360.00 | 450.00 | 2000.00 | 30.00 | 0.50 | -12.04 |
| 440.00 | 480.00 | 900.00 | 32.00 | 1.11 | -5.11 |
| 420.00 | 480.00 | 800.00 | 40.00 | 1.25 | -4.08 |
| 600.00 | 540.00 | 25.00 | 28.00 | 40.00 | 26.02 |
| 190.00 | 270.00 | 375.00 | 46.00 | 2.67 | 2.50 |
| 185.00 | 240.00 | 440.00 | 48.00 | 2.27 | 1.11 |
| 160.00 | 325.00 | 408.00 | 45.00 | 2.45 | 1.77 |
| 150.00 | 350.00 | 430.00 | 39.00 | 2.33 | 1.31 |
| 140.00 | 380.00 | 460.00 | 39.00 | 2.17 | 0.72 |
| 110.00 | 410.00 | 1580.00 | 35.00 | 0.63 | -9.99 |

| | | | | | |
|---|---|---|---|---|---|
| 90.00 | 430.00 | 1600.00 | 34.00 | 0.63 | -10.10 |
| 70.00 | 460.00 | 1600.00 | 35.00 | 0.63 | -10.10 |
| 40.00 | 470.00 | 1250.00 | 25.00 | 0.80 | -7.96 |
| 190.00 | 240.00 | 375.00 | 46.00 | 2.67 | 2.50 |
| 155.00 | 255.00 | 285.00 | 44.00 | 3.51 | 4.88 |
| 100.00 | 260.00 | 375.00 | 38.00 | 2.67 | 2.50 |
| 70.00 | 265.00 | 500.00 | 38.50 | 2.00 | 0.00 |
| 40.00 | 270.00 | 780.00 | 34.00 | 1.28 | -3.86 |
| 10.00 | 270.00 | 1570.00 | 31.00 | 0.64 | -9.94 |
| -20.00 | 270.00 | 2000.00 | 32.00 | 0.50 | -12.04 |
| -50.00 | 270.00 | 2900.00 | 31.00 | 0.34 | -15.27 |
| -80.00 | 270.00 | 2950.00 | 32.00 | 0.34 | -15.42 |
| 320.00 | 0.00 | 5500.00 | 37.00 | 0.18 | -20.83 |
| 120.00 | -30.00 | 3000.00 | 32.00 | 0.33 | -15.56 |
| 80.00 | -60.00 | 2000.00 | 40.00 | 0.50 | -12.04 |
| 170.00 | -15.00 | 1050.00 | 34.00 | 0.95 | -6.44 |
| 150.00 | 0.00 | 2000.00 | 35.00 | 0.50 | -12.04 |

```
     TITLE NORTHBAY SURVEY 1984/85:   EM31 CONTOURS,  500 OM
BACK
     IDXY 50,11,3,1,,3,0,0,0,,'(2F10.2,10X,F10.2)'
     POST 2,0,.05,.05,0
     DEVICE 6,'GREENHOUSE',1200.,33.5
     BOX 25,4,25,4,0,350,300,1,.25
     BXEX 350,650,300,500
     SIZC 0,25.651,25.651
     GRID 1,15,15,0,0,0,0
     EXTREMES 350,650,300,500
     CINT 0,-12,4,12,,0,,4
     CONTOUR
     PERFORM
     STOP
```

| NORTH(m) | WEST(m) | EM(mS/m) | Norlize |
|---|---|---|---|
| 600.00 | 0.00 | 10.00 | 13.98 |
| 595.00 | 0.00 | 1.50 | -2.50 |
| 590.00 | 0.00 | 1.00 | -6.02 |
| 585.00 | 0.00 | 0.60 | -10.46 |
| 580.00 | 0.00 | 0.90 | -6.94 |
| 575.00 | 0.00 | 0.60 | -10.46 |
| 570.00 | 0.00 | 0.40 | -13.98 |
| 565.00 | 0.00 | 0.30 | -16.48 |
| 560.00 | 0.00 | 0.10 | -26.02 |
| 555.00 | 0.00 | 0.10 | -26.02 |
| 550.00 | 0.00 | 0.20 | -20.00 |
| 545.00 | 0.00 | 0.20 | -20.00 |
| 540.00 | 0.00 | 0.10 | -26.02 |
| 535.00 | 0.00 | 0.20 | -20.00 |
| 530.00 | 0.00 | 0.20 | -20.00 |
| 525.00 | 0.00 | 0.10 | -26.02 |
| 520.00 | 0.00 | 0.30 | -16.48 |
| 515.00 | 0.00 | 0.20 | -20.00 |
| 510.00 | 0.00 | 0.40 | -13.98 |
| 505.00 | 0.00 | 0.60 | -10.46 |
| 495.00 | 0.00 | 0.60 | -10.46 |
| 490.00 | 0.00 | 0.90 | -6.94 |
| 485.00 | 0.00 | 0.40 | -13.98 |
| 480.00 | 0.00 | 0.50 | -12.04 |
| 470.00 | 0.00 | 0.40 | -13.98 |
| 465.00 | 0.00 | 0.20 | -20.00 |
| 460.00 | 0.00 | 1.20 | -4.44 |
| 455.00 | 0.00 | 0.60 | -10.46 |
| 445.00 | 0.00 | 0.10 | -26.02 |
| 440.00 | 0.00 | 0.10 | -26.02 |
| 435.00 | 0.00 | 0.10 | -26.02 |
| 430.00 | 0.00 | 0.60 | -10.46 |
| 425.00 | 0.00 | 0.90 | -6.94 |
| 420.00 | 0.00 | 0.60 | -10.46 |
| 415.00 | 0.00 | 0.30 | -16.48 |
| 410.00 | 0.00 | 0.30 | -16.48 |
| 405.00 | 0.00 | 0.10 | -26.02 |
| 400.00 | 0.00 | 0.20 | -20.00 |
| 395.00 | 0.00 | 0.10 | -26.02 |
| 390.00 | 0.00 | 0.20 | -20.00 |
| 385.00 | 0.00 | 0.20 | -20.00 |
| 380.00 | 0.00 | 0.20 | -20.00 |
| 375.00 | 0.00 | 0.10 | -26.02 |
| 370.00 | 0.00 | 0.10 | -26.02 |
| 365.00 | 0.00 | 0.10 | -26.02 |
| 360.00 | 0.00 | 0.30 | -16.48 |
| 600.00 | 240.00 | 3.00 | 3.52 |
| 595.00 | 240.00 | 11.00 | 14.81 |
| 590.00 | 240.00 | 2.80 | 2.92 |
| 585.00 | 240.00 | 12.50 | 15.92 |
| 580.00 | 240.00 | 0.60 | -10.46 |
| 575.00 | 240.00 | 0.70 | -9.12 |

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570.00     240.00      0.40     -13.98
565.00     240.00      0.20     -20.00
560.00     240.00      0.10     -26.02
550.00     240.00      0.10     -26.02
545.00     240.00      0.10     -26.02
540.00     240.00      0.10     -26.02
535.00     240.00      0.10     -26.02
530.00     240.00      0.10     -26.02
520.00     240.00      0.20     -20.00
505.00     240.00      3.50       4.86
500.00     240.00      1.20      -4.44
495.00     240.00      1.50      -2.50
490.00     240.00      1.00      -6.02
485.00     240.00      0.50     -12.04
480.00     240.00      0.40     -13.98
475.00     240.00      0.40     -13.98
470.00     240.00      0.40     -13.98
465.00     240.00      0.40     -13.98
460.00     240.00      0.50     -12.04
455.00     240.00      0.50     -12.04
450.00     240.00      0.90      -6.94
445.00     240.00      1.00      -6.02
440.00     240.00      1.30      -3.74
435.00     240.00      1.90      -0.45
430.00     240.00      3.00       3.52
425.00     240.00      3.90       5.80
420.00     240.00      6.20       9.83
415.00     240.00      7.10      11.00
410.00     240.00      7.70      11.71
405.00     240.00      7.90      11.93
400.00     240.00      8.40      12.46
395.00     240.00      8.20      12.26
390.00     240.00      7.00      10.88
385.00     240.00      6.10       9.69
380.00     240.00      5.60       8.94
375.00     240.00      5.20       8.30
370.00     240.00      5.80       9.25
365.00     240.00      4.10       6.24
360.00     240.00      2.00       0.00
340.00     240.00      0.70      -9.12
335.00     240.00      0.90      -6.94
330.00     240.00      0.60     -10.46
325.00     240.00      1.30      -3.74
320.00     240.00      1.00      -6.02
315.00     240.00      9.50      13.53
310.00     240.00      0.95      -6.47
305.00     240.00      1.05      -5.60
300.00     240.00      1.00      -6.02
295.00     240.00      0.90      -6.94
290.00     240.00      1.10      -5.19
285.00     240.00      0.90      -6.94
280.00     240.00      0.80      -7.96
275.00     240.00      0.80      -7.96
270.00     240.00      0.75      -8.52
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265.00     240.00      0.65     -9.76
260.00     240.00      0.65     -9.76
255.00     240.00      0.55    -11.21
250.00     240.00      0.55    -11.21
245.00     240.00      0.45    -12.96
240.00     240.00      0.40    -13.98
235.00     240.00      0.35    -15.14
230.00     240.00      0.35    -15.14
225.00     240.00      0.10    -26.02
220.00     240.00      0.15    -22.50
215.00     240.00      0.15    -22.50
210.00     240.00      0.10    -26.02
205.00     240.00      0.15    -22.50
200.00     240.00      0.10    -26.02
195.00     240.00      0.05    -32.04
190.00     240.00      0.05    -32.04
185.00     240.00      0.10    -26.02
180.00     240.00      0.05    -32.04
610.00       0.00      4.50      7.04
610.00      15.00      3.20      4.08
610.00      36.00      2.60      2.28
610.00      45.00      2.20      0.83
610.00      60.00      1.80     -0.92
610.00      75.00      1.50     -2.50
610.00      96.00      2.20      0.83
610.00     105.00      2.20      0.83
610.00     120.00      3.00      3.52
610.00     135.00      2.00      0.00
610.00     150.00      2.00      0.00
610.00     165.00      1.50     -2.50
610.00     180.00      1.80     -0.92
610.00     195.00      2.00      0.00
610.00     210.00      1.80     -0.92
610.00     225.00      1.00     -6.02
610.00     240.00      1.20     -4.44
610.00     255.00      1.50     -2.50
610.00     270.00      1.80     -0.92
610.00     285.00      1.50     -2.50
610.00     300.00      1.10     -5.19
480.00     390.00     20.50     20.21
450.00     390.00      8.40     12.46
420.00     390.00      9.40     13.44
390.00     390.00      4.20      6.44
360.00     390.00      2.80      2.92
330.00     390.00      2.20      0.83
420.00     120.00      0.30    -16.48
420.00     150.00      0.50    -12.04
420.00     180.00      0.60    -10.46
420.00     210.00      1.40     -3.10
420.00     240.00      6.60     10.37
420.00     270.00      5.00      7.96
420.00     300.00      7.00     10.88
420.00     360.00      7.30     11.25
450.00      30.00      0.70     -9.12
```

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450.00       60.00        0.50      -12.04
450.00       90.00        0.60      -10.46
450.00      120.00        0.30      -16.48
450.00      150.00        0.40      -13.98
450.00      180.00        0.50      -12.04
450.00      210.00        0.30      -16.48
450.00      240.00        1.00       -6.02
160.00      120.00        3.50        4.86
150.00      120.00        4.50        7.04
145.00      120.00        6.50       10.24
140.00      120.00        5.00        7.96
135.00      120.00        4.50        7.04
125.00      120.00        1.50       -2.50
600.00       60.00        2.40        1.58
595.00       60.00        2.50        1.94
590.00       60.00        2.60        2.28
585.00       60.00        2.50        1.94
580.00       60.00        3.50        4.86
575.00       60.00        3.00        3.52
570.00       60.00        2.80        2.92
565.00       60.00        3.50        4.86
560.00       60.00        7.00       10.88
555.00       60.00        9.00       13.06
550.00       60.00       14.00       16.90
545.00       60.00       15.00       17.50
330.00      390.00        1.20       -4.44
335.00      390.00        1.20       -4.44
340.00      390.00        1.40       -3.10
345.00      390.00        1.20       -4.44
350.00      390.00        1.20       -4.44
355.00      390.00        1.20       -4.44
360.00      390.00        1.60       -1.94
365.00      390.00        1.50       -2.50
370.00      390.00        1.60       -1.94
375.00      390.00        1.70       -1.41
380.00      390.00        1.70       -1.41
385.00      390.00        1.70       -1.41
390.00      390.00        2.00        0.00
395.00      390.00        3.00        3.52
400.00      390.00        3.50        4.86
405.00      390.00        4.00        6.02
415.00      390.00        4.50        7.04
420.00      390.00        5.80        9.25
430.00      390.00        6.80       10.63
425.00      390.00        6.70       10.50
560.00      390.00       23.00       21.21
565.00      390.00       23.00       21.21
570.00      390.00       29.00       23.23
600.00      420.00       65.00       30.24
615.00      435.00       50.00       27.96
625.00      440.00       50.00       27.96
610.00      390.00       30.00       23.52
610.00      375.00       17.00       18.59
610.00      360.00       15.00       17.50
```

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610.00     330.00      5.00      7.96
610.00     315.00      0.10    -26.02
600.00     300.00      3.00      3.52
595.00     300.00      0.10    -26.02
590.00     300.00      2.00      0.00
585.00     300.00      0.10    -26.02
580.00     300.00      0.10    -26.02
540.00     300.00      0.10    -26.02
535.00     300.00      0.10    -26.02
530.00     300.00      0.10    -26.02
525.00     300.00      0.10    -26.02
500.00     300.00      0.50    -12.04
495.00     300.00      2.50      1.94
490.00     300.00      3.50      4.86
485.00     300.00      3.50      4.86
480.00     300.00      3.20      4.08
475.00     300.00      4.40      6.85
470.00     300.00      4.40      6.85
465.00     300.00      7.00     10.88
460.00     300.00     13.50     16.59
455.00     300.00     15.00     17.50
450.00     300.00      6.80     10.63
445.00     300.00      6.80     10.63
440.00     300.00      6.00      9.54
435.00     300.00      6.20      9.83
430.00     300.00      6.00      9.54
425.00     300.00      6.00      9.54
420.00     300.00      5.20      8.30
415.00     300.00      5.00      7.96
410.00     300.00      5.20      8.30
405.00     300.00      4.60      7.23
400.00     300.00      4.50      7.04
395.00     300.00      5.00      7.96
390.00     300.00      4.60      7.23
385.00     300.00      5.00      7.96
380.00     300.00      4.90      7.78
375.00     300.00      4.50      7.04
370.00     300.00      3.80      5.58
365.00     300.00      3.80      5.58
360.00     300.00      3.40      4.61
355.00     300.00      3.20      4.08
350.00     300.00      3.00      3.52
345.00     300.00      2.80      2.92
340.00     300.00      2.60      2.28
335.00     300.00      2.20      0.83
330.00     300.00      2.00      0.00
325.00     300.00      1.90     -0.45
320.00     300.00      0.70     -9.12
600.00     330.00     12.00     15.56
600.00     210.00      8.00     12.04
595.00     210.00      2.00      0.00
450.00     210.00      0.10    -26.02
445.00     210.00      0.20    -20.00
440.00     210.00      0.10    -26.02
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| | | | |
|---|---|---|---|
| 435.00 | 210.00 | 0.20 | -20.00 |
| 430.00 | 210.00 | 0.30 | -16.48 |
| 425.00 | 210.00 | 0.40 | -13.98 |
| 420.00 | 210.00 | 0.80 | -7.96 |
| 415.00 | 210.00 | 1.60 | -1.94 |
| 410.00 | 210.00 | 2.80 | 2.92 |
| 405.00 | 210.00 | 4.20 | 6.44 |
| 400.00 | 210.00 | 5.00 | 7.96 |
| 395.00 | 210.00 | 5.00 | 7.96 |
| 390.00 | 210.00 | 5.00 | 7.96 |
| 385.00 | 210.00 | 4.50 | 7.04 |
| 380.00 | 210.00 | 4.20 | 6.44 |
| 375.00 | 210.00 | 3.60 | 5.11 |
| 370.00 | 210.00 | 3.00 | 3.52 |
| 390.00 | 165.00 | 1.20 | -4.44 |
| 390.00 | 170.00 | 1.65 | -1.67 |
| 390.00 | 175.00 | 2.35 | 1.40 |
| 390.00 | 180.00 | 2.70 | 2.61 |
| 390.00 | 185.00 | 3.20 | 4.08 |
| 390.00 | 190.00 | 3.90 | 5.80 |
| 390.00 | 195.00 | 4.10 | 6.24 |
| 390.00 | 200.00 | 4.10 | 6.24 |
| 390.00 | 205.00 | 4.60 | 7.23 |
| 390.00 | 210.00 | 4.80 | 7.60 |
| 390.00 | 215.00 | 5.00 | 7.96 |
| 390.00 | 220.00 | 5.20 | 8.30 |
| 390.00 | 225.00 | 5.50 | 8.79 |
| 390.00 | 230.00 | 5.60 | 8.94 |
| 390.00 | 235.00 | 5.60 | 8.94 |
| 390.00 | 240.00 | 5.60 | 8.94 |
| 390.00 | 245.00 | 5.40 | 8.63 |
| 390.00 | 250.00 | 5.00 | 7.96 |
| 390.00 | 255.00 | 4.50 | 7.04 |
| 390.00 | 260.00 | 4.40 | 6.85 |
| 390.00 | 265.00 | 4.30 | 6.65 |
| 390.00 | 270.00 | 4.80 | 7.60 |
| 390.00 | 275.00 | 5.40 | 8.63 |
| 390.00 | 280.00 | 5.70 | 9.10 |
| 390.00 | 285.00 | 5.70 | 9.10 |
| 390.00 | 290.00 | 5.50 | 8.79 |
| 390.00 | 295.00 | 5.20 | 8.30 |
| 390.00 | 300.00 | 5.00 | 7.96 |
| 390.00 | 305.00 | 4.50 | 7.04 |
| 390.00 | 310.00 | 4.20 | 6.44 |
| 390.00 | 315.00 | 4.10 | 6.24 |
| 390.00 | 320.00 | 4.00 | 6.02 |
| 390.00 | 325.00 | 4.10 | 6.24 |
| 390.00 | 330.00 | 7.00 | 10.88 |
| 390.00 | 335.00 | 0.10 | -26.02 |
| 390.00 | 340.00 | 2.90 | 3.23 |
| 390.00 | 345.00 | 4.10 | 6.24 |
| 390.00 | 350.00 | 2.90 | 3.23 |
| 390.00 | 355.00 | 2.70 | 2.61 |
| 390.00 | 360.00 | 3.00 | 3.52 |

```
390.00     365.00       3.10      3.81
390.00     370.00       3.10      3.81
390.00     375.00       4.20      6.44
390.00     380.00       4.30      6.65
390.00     385.00       4.50      7.04
390.00     390.00       3.50      4.86
390.00     395.00       4.00      6.02
390.00     400.00       3.50      4.86
390.00     405.00       3.30      4.35
390.00     410.00       3.00      3.52
390.00     415.00       2.70      2.61
390.00     420.00       2.90      3.23
510.00     390.00      22.00     20.83
510.00     395.00      23.00     21.21
510.00     400.00      24.00     21.58
510.00     405.00      24.50     21.76
510.00     410.00      26.00     22.28
510.00     415.00      30.00     23.52
510.00     420.00      39.00     25.80
510.00     425.00      48.00     27.60
510.00     430.00      58.00     29.25
510.00     385.00      14.50     17.21
510.00     380.00      13.60     16.65
510.00     375.00      11.50     15.19
510.00     370.00      10.00     13.98
510.00     365.00       9.00     13.06
510.00     360.00       9.80     13.80
510.00     355.00      10.00     13.98
510.00     350.00      13.50     16.59
510.00     345.00      22.00     20.83
510.00     340.00       0.10    -26.02
510.00     335.00      22.50     21.02
510.00     330.00      12.50     15.92
510.00     325.00       8.60     12.67
510.00     320.00       5.80      9.25
510.00     315.00       4.30      6.65
510.00     310.00       2.80      2.92
510.00     305.00       2.00      0.00
510.00     300.00       1.50     -2.50
540.00     300.00       1.30     -3.74
540.00     305.00       1.50     -2.50
540.00     310.00       2.20      0.83
540.00     315.00       3.10      3.81
540.00     320.00       3.40      4.61
540.00     325.00       3.60      5.11
540.00     330.00       5.50      8.79
540.00     335.00       9.00     13.06
540.00     340.00      19.00     19.55
540.00     345.00       0.10    -26.02
540.00     350.00      15.00     17.50
540.00     355.00      11.00     14.81
540.00     360.00       9.00     13.06
540.00     365.00      10.00     13.98
540.00     370.00      10.50     14.40
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| | | | |
|---|---|---|---|
| 540.00 | 375.00 | 12.00 | 15.56 |
| 540.00 | 380.00 | 13.00 | 16.26 |
| 540.00 | 385.00 | 16.20 | 18.17 |
| 540.00 | 390.00 | 20.00 | 20.00 |
| 540.00 | 395.00 | 23.50 | 21.40 |
| 540.00 | 400.00 | 25.50 | 22.11 |
| 540.00 | 405.00 | 30.00 | 23.52 |
| 540.00 | 410.00 | 38.00 | 25.58 |
| 540.00 | 415.00 | 44.00 | 26.85 |
| 540.00 | 420.00 | 47.00 | 27.42 |
| 570.00 | 390.00 | 15.00 | 17.50 |
| 570.00 | 395.00 | 16.00 | 18.06 |
| 570.00 | 400.00 | 23.00 | 21.21 |
| 570.00 | 405.00 | 33.00 | 24.35 |
| 570.00 | 410.00 | 38.00 | 25.58 |
| 570.00 | 415.00 | 46.00 | 27.23 |
| 570.00 | 270.00 | 1.00 | -6.02 |
| 570.00 | 275.00 | 1.50 | -2.50 |
| 570.00 | 315.00 | 3.00 | 3.52 |
| 570.00 | 320.00 | 2.80 | 2.92 |
| 570.00 | 325.00 | 3.60 | 5.11 |
| 570.00 | 330.00 | 5.20 | 8.30 |
| 570.00 | 335.00 | 7.00 | 10.88 |
| 570.00 | 340.00 | 15.00 | 17.50 |
| 570.00 | 345.00 | 7.00 | 10.88 |
| 570.00 | 350.00 | 19.50 | 19.78 |
| 570.00 | 355.00 | 11.00 | 14.81 |
| 570.00 | 360.00 | 9.00 | 13.06 |
| 570.00 | 365.00 | 13.00 | 16.26 |
| 570.00 | 370.00 | 16.00 | 18.06 |
| 570.00 | 375.00 | 20.00 | 20.00 |
| 570.00 | 380.00 | 19.00 | 19.55 |
| 570.00 | 385.00 | 18.50 | 19.32 |
| 450.00 | 325.00 | 15.00 | 17.50 |
| 450.00 | 330.00 | 24.00 | 21.58 |
| 450.00 | 335.00 | 4.50 | 7.04 |
| 450.00 | 340.00 | 22.00 | 20.83 |
| 450.00 | 345.00 | 15.00 | 17.50 |
| 450.00 | 350.00 | 10.50 | 14.40 |
| 450.00 | 355.00 | 9.00 | 13.06 |
| 450.00 | 360.00 | 7.50 | 11.48 |
| 450.00 | 365.00 | 7.00 | 10.88 |
| 450.00 | 370.00 | 6.60 | 10.37 |
| 450.00 | 375.00 | 6.80 | 10.63 |
| 450.00 | 380.00 | 6.80 | 10.63 |
| 450.00 | 385.00 | 6.80 | 10.63 |
| 450.00 | 390.00 | 6.40 | 10.10 |
| 450.00 | 395.00 | 6.40 | 10.10 |
| 450.00 | 400.00 | 6.80 | 10.63 |
| 450.00 | 405.00 | 7.60 | 11.60 |
| 450.00 | 410.00 | 9.10 | 13.16 |
| 450.00 | 415.00 | 10.20 | 14.15 |
| 450.00 | 420.00 | 13.00 | 16.26 |
| 450.00 | 425.00 | 15.50 | 17.79 |

| | | | |
|---|---|---|---|
| 450.00 | 430.00 | 15.00 | 17.50 |
| 450.00 | 435.00 | 16.50 | 18.33 |
| 450.00 | 440.00 | 16.00 | 18.06 |
| 450.00 | 445.00 | 14.50 | 17.21 |
| 450.00 | 450.00 | 14.00 | 16.90 |
| 450.00 | 455.00 | 13.00 | 16.26 |
| 450.00 | 460.00 | 11.50 | 15.19 |
| 450.00 | 465.00 | 9.50 | 13.53 |
| 450.00 | 470.00 | 8.00 | 12.04 |
| 480.00 | 300.00 | 5.60 | 8.94 |
| 480.00 | 305.00 | 6.20 | 9.83 |
| 480.00 | 310.00 | 8.50 | 12.57 |
| 480.00 | 315.00 | 12.00 | 15.56 |
| 480.00 | 320.00 | 15.00 | 17.50 |
| 480.00 | 325.00 | 15.50 | 17.79 |
| 480.00 | 330.00 | 23.00 | 21.21 |
| 480.00 | 235.00 | 36.00 | 25.11 |
| 480.00 | 340.00 | 8.00 | 12.04 |
| 480.00 | 345.00 | 22.50 | 21.02 |
| 480.00 | 350.00 | 16.50 | 18.33 |
| 480.00 | 355.00 | 15.00 | 17.50 |
| 480.00 | 360.00 | 14.50 | 17.21 |
| 480.00 | 365.00 | 15.00 | 17.50 |
| 480.00 | 370.00 | 18.50 | 19.32 |
| 480.00 | 375.00 | 22.00 | 20.83 |
| 480.00 | 380.00 | 22.00 | 20.83 |
| 480.00 | 385.00 | 24.00 | 21.58 |
| 480.00 | 390.00 | 21.00 | 20.42 |
| 480.00 | 395.00 | 21.00 | 20.42 |
| 480.00 | 400.00 | 20.00 | 20.00 |
| 480.00 | 405.00 | 23.00 | 21.21 |
| 560.00 | 330.00 | 4.00 | 6.02 |
| 555.00 | 330.00 | 4.30 | 6.65 |
| 550.00 | 330.00 | 4.00 | 6.02 |
| 480.00 | 410.00 | 27.00 | 22.61 |
| 480.00 | 415.00 | 30.00 | 23.52 |
| 480.00 | 420.00 | 35.00 | 24.86 |
| 480.00 | 425.00 | 40.00 | 26.02 |
| 480.00 | 430.00 | 42.50 | 26.55 |
| 535.60 | 386.00 | 15.00 | 17.50 |
| 531.60 | 389.00 | 17.20 | 18.69 |
| 527.60 | 392.00 | 19.00 | 19.55 |
| 523.60 | 395.00 | 18.50 | 19.32 |
| 519.60 | 398.00 | 22.00 | 20.83 |
| 515.60 | 401.00 | 20.50 | 20.21 |
| 511.60 | 404.00 | 24.00 | 21.58 |
| 507.60 | 407.00 | 27.00 | 22.61 |
| 503.60 | 410.00 | 27.00 | 22.61 |
| 499.60 | 413.00 | 25.00 | 21.94 |
| 495.60 | 416.00 | 25.00 | 21.94 |
| 491.60 | 419.00 | 24.90 | 21.90 |
| 487.60 | 422.00 | 23.50 | 21.40 |
| 483.60 | 425.00 | 22.50 | 21.02 |
| 479.60 | 428.00 | 16.00 | 18.06 |

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476.00     431.00     18.00     19.08
471.70     434.00     15.00     17.50
467.70     437.00      8.30     12.36
463.70     440.00      7.00     10.88
459.70     443.00      7.50     11.48
455.70     446.00      5.50      8.79
451.70     449.00      4.00      6.02
447.70     452.00      2.80      2.92
443.70     455.00      7.30     11.25
539.60     383.00     13.00     16.26
543.60     380.00      9.50     13.53
547.60     377.00     11.00     14.81
551.60     374.00      9.00     13.06
555.60     371.00     10.00     13.98
559.60     368.00     11.00     14.81
563.60     365.00      9.50     13.53
567.60     362.00      8.00     12.04
571.60     359.00      9.00     13.06
575.60     356.00     11.00     14.81
579.60     353.00     15.00     17.50
583.60     350.00     22.00     20.83
585.60     347.00      5.00      7.96
589.60     344.00     24.00     21.58
593.60     341.00     30.00     23.52
597.60     338.00     12.00     15.56
601.60     335.00     13.00     16.26
605.60     332.00      7.50     11.48
609.60     329.00      6.00      9.54
613.60     326.00      3.00      3.52
617.60     323.00      1.50     -2.50
621.60     320.00      0.10    -26.02
625.60     317.00      0.10    -26.02
629.60     314.00      1.00     -6.02
495.00     364.00     10.50     14.40
491.00     367.00     11.00     14.81
487.00     370.00     10.60     14.49
483.00     373.00     13.00     16.26
479.00     376.00     16.00     18.06
475.00     379.00     19.40     19.74
471.00     382.00     21.00     20.42
467.00     385.00     18.00     19.08
463.00     388.00     11.50     15.19
459.00     391.00      9.00     13.06
455.00     394.00      7.00     10.88
451.00     397.00      6.50     10.24
447.00     400.00      5.00      7.96
443.00     403.00      5.00      7.96
439.00     406.00      5.00      7.96
435.00     409.00      5.20      8.30
431.00     412.00      5.60      8.94
427.00     415.00      6.00      9.54
423.00     418.00      5.50      8.79
419.00     421.00      4.50      7.04
415.00     424.00      4.00      6.02
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411.00     427.00      3.00       3.52
407.00     430.00      2.50       1.94
403.00     433.00      2.00       0.00
399.00     436.00      1.50      -2.50
395.00     439.00      1.20      -4.44
391.00     442.00      1.50      -2.50
387.00     445.00      1.00      -6.02
383.00     448.00      1.20      -4.44
379.00     451.00      1.50      -2.50
375.00     454.00      1.50      -2.50
499.00     361.00     12.00      15.56
503.00     358.00     16.80      18.49
507.00     355.00     30.00      23.52
511.00     352.00      0.10     -26.02
515.00     349.00     30.00      23.52
519.00     346.00     21.00      20.42
523.00     343.00     11.00      14.81
527.00     340.00      6.90      10.76
531.00     337.00      5.30       8.46
535.00     334.00      3.50       4.86
499.00     420.00     27.00      22.61
502.00     424.00     30.20      23.58
504.60     428.00      0.10     -26.02
493.00     412.00     24.50      21.76
490.00     408.00     22.20      20.91
487.00     404.00     17.60      18.89
484.00     400.00     14.30      17.09
481.00     396.00     14.20      17.03
478.00     392.00     13.40      16.52
474.00     388.00      8.50      12.57
471.00     384.00      9.80      13.80
468.00     380.00      9.10      13.16
465.00     376.00     10.50      14.40
462.00     372.00      9.00      13.06
459.00     368.00     12.10      15.64
456.00     364.00      7.10      11.00
```

# Appendix D

# SEISMIC RAW DATA

```
1
         NORTHINGI(M)   WESTING(M)   DEPTH(M)  SOURCE*
              360.00      120.00      332.11       1
              360.00      130.00      332.70       1
              360.00      140.00      332.94       1
              360.00      150.00      332.55       1
              360.00      160.00      332.18       1
              360.00      170.00      332.37       1
              360.00      180.00      331.70       1
              360.00      190.00      331.51       1
              360.00      200.00      330.95       1
              360.00      210.00      330.60       1
              360.00      220.00      330.54       1
              360.00      230.00      329.85       1
              420.00      110.00      331.85       1
              420.00      120.00      333.31       1
              420.00      130.00      332.26       1
              420.00      140.00      331.17       1
              420.00      150.00      330.00       1
              420.00      160.00      330.60       1
              420.00      170.00      328.65       1
              420.00      180.00      329.51       1
              420.00      190.00      328.87       1
              420.00      200.00      328.79       1
              420.00      210.00      327.37       1
              420.00      220.00      326.63       1
              460.00      180.00      328.43       1
              450.00      180.00      329.55       1
              440.00      180.00      328.22       1
              430.00      180.00      328.09       1
              420.00      180.00      328.67       1
              410.00      180.00      329.17       1
              400.00      180.00      329.59       1
              390.00      180.00      328.87       1
              380.00      180.00      329.05       1
              370.00      180.00      329.13       1
              360.00      180.00      330.65       1
              350.00      180.00      333.89       1
              360.00      255.00      326.46       1
              360.00      270.00      324.96       1
              360.00      285.00      326.15       1
              260.00      300.00      325.83       1
              360.00      315.00      327.14       1
              360.00      330.00      326.72       1
              360.00      345.00      327.51       1
              360.00      360.00      327.08       1
              360.00      375.00      326.15       1
              360.00      390.00      323.77       1
              360.00      405.00      321.39       1
              360.00      420.00      320.50       1
              420.00      240.00      328.67       1
              420.00      255.00      329.96       1
              420.00      270.00      326.56       1
              420.00      285.00      329.05       1
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| | | | |
|---|---|---|---|
| 190.00 | 96.40 | 328.07 | 2 |
| 187.00 | 100.40 | 327.74 | 2 |
| 184.00 | 104.40 | 329.21 | 2 |
| 181.00 | 108.40 | 328.45 | 2 |
| 178.00 | 112.40 | 327.17 | 2 |
| 175.00 | 116.40 | 327.12 | 2 |
| 172.00 | 120.40 | 325.70 | 2 |
| 169.00 | 124.30 | 324.48 | 2 |
| 166.00 | 128.30 | 323.41 | 2 |
| 157.00 | 140.30 | 323.30 | 2 |
| 188.00 | 169.10 | 323.91 | 2 |
| 194.00 | 161.10 | 324.83 | 2 |
| 197.00 | 157.10 | 325.19 | 2 |
| 200.00 | 153.10 | 326.30 | 2 |
| 203.00 | 149.10 | 327.69 | 2 |
| 206.00 | 145.10 | 327.90 | 2 |
| 212.00 | 137.10 | 327.40 | 2 |
| 215.00 | 133.10 | 327.70 | 2 |
| 218.00 | 129.10 | 328.40 | 2 |
| 221.00 | 125.10 | 328.60 | 2 |
| 224.00 | 121.10 | 329.06 | 2 |
| 230.00 | 113.20 | 325.60 | 2 |
| 192.00 | 110.40 | 326.97 | 2 |
| 200.00 | 116.40 | 329.06 | 2 |
| 208.00 | 122.40 | 325.01 | 2 |
| 340.00 | 240.00 | 328.32 | 2 |
| 420.00 | 80.00 | 334.00 | 2 |
| 240.00 | 200.00 | 328.00 | 2 |
| 210.00 | 230.00 | 325.00 | 2 |
| 160.00 | 250.00 | 328.30 | 2 |
| 120.00 | 20.00 | 335.10 | 2 |
| 300.00 | 60.00 | 328.50 | 2 |
| 360.00 | 50.00 | 334.00 | 2 |
| 480.00 | 60.00 | 342.00 | 4 |
| 160.00 | 280.00 | 327.00 | 2 |

* 1 = GEOPHYSICAL DATA
2 = BOREHOLE DATA
3 = GEOLOGICAL DATA

```
SOUNDING  3                          NORTH BAY  SEISMIC EISMIC
PHONES     FROM:         180.00                 TO: 240

                                              SHOT AT:               SHOT AT:
 NORTHING    WESTING   ELEV.
   (m)        (m)        (m)       DIS.(m)      TIME      DIS.(m)     TIME
   240.00     210.00       0.00       2.00      16.00     110.00     49.50
   235.00     210.00       0.00       5.00       0.00     100.00     47.00
   230.00     210.00       0.00      10.00      23.00      90.00     46.00
   225.00     210.00       0.00      15.00      26.00      80.00     43.00
   220.00     210.00       0.00      20.00      29.50      70.00     42.50
   215.00     210.00       0.00      25.00      32.00      60.00     42.00
   210.00     210.00       0.00      30.00      33.00      55.00     41.25
   205.00     210.00       0.00      35.00      36.00      50.00     39.00
   200.00     210.00       0.00      40.00      35.00      45.00     38.50
   195.00     210.00       0.00      45.00      38.50      40.00     36.00
   190.00     210.00       0.00      50.00      36.00      35.00     35.00
   185.00     210.00       0.00      55.00      41.50      30.00     33.00
   180.00     210.00       0.00      60.00      37.00      25.00     29.00
                                     70.00      37.00      20.00     26.00
                                     80.00      38.00      15.00     22.75




                                                DEPT.
  T1(-)    Vel.(2)    COS(C)      T2(+)     (m)
 -33.50    1481.48    9909.96     20.00      5.05
 -47.00     833.33                 1.50      0.38
 -23.00    3333.33                23.50      5.93
 -17.00    5000.00                23.50      5.93
 -13.00    6666.67                26.50      6.69
 -10.00   11428.57                28.50      7.20
  -8.25    3809.52                28.75      7.26
  -3.00   40000.00                29.50      7.45
  -3.50    3333.33                28.00      7.07
   2.50   13333.33                29.00      7.32
   1.00    2666.67                25.50      6.44
   8.50   40000.00                29.00      7.32
   8.00    6666.67                20.50      5.18
  11.00    4705.88                17.50      4.42
  15.25    4210.53                15.25      3.85
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profile4                                    NORTH BAY SEISMIC
PHONES FROM :120                             TO :230


NORTHING  WESTING             CORR.                          CORR.
  (m)      (m)       ELEV.    ELEV.     DIST.      TIME      TIME     DIST.
  240.00    120.00  337.31     2.55      2.00     25.00     18.65      2.00
  240.00    130.00  337.30     2.54     12.00     23.00     16.67     12.00
  240.00    140.00  337.34     2.58     20.00     24.00     17.57     20.00
  240.00    150.00  337.35     2.59     30.00     27.00     20.55     30.00
  240.00    160.00  337.58     2.82     40.00     31.00     23.97     40.00
  240.00    170.00  337.57     2.81     50.00     32.00     25.00     50.00
  240.00    180.00  336.50     1.74     60.00     33.00     28.66     60.00
  240.00    190.00  336.51     1.75     70.00     35.00     30.64     70.00
  240.00    200.00  336.34     1.58     80.00     38.00     34.06     80.00
  240.00    210.00  336.79     2.03     90.00     42.00     36.94     90.00
  240.00    220.00  337.54     2.78    100.00     46.00     39.07    100.00
  240.00    230.00  338.04     3.28    110.00     52.00     43.83    110.00




                                  V(1)=400

   T(-)     Vel.(2)   Vav.       Vel.(1)      COS(c)      T(+)       DEPT.
  -28.00  20000.00 5000.00      400.00        1.00      13.23        2.65
  -29.00   6666.67 5000.00      400.00        1.00      10.34        2.06
  -26.00   5000.00 5000.00      400.00        1.00       9.14        1.82
  -22.00   4000.00 5000.00      400.00        1.00      11.09        2.21
  -17.00   6666.67 5000.00      400.00        1.00      12.95        2.58
  -14.00   5000.00 5000.00      400.00        1.00      12.00        2.39
  -10.00   6666.67 5000.00      400.00        1.00      15.33        3.06
   -7.00   5000.00 5000.00      400.00        1.00      16.28        3.25
   -3.00   5000.00 5000.00      400.00        1.00      19.13        3.81
    1.00   5000.00 5000.00      400.00        1.00      20.88        4.16
    5.00   3333.33 5000.00      400.00        1.00      21.14        4.22
   11.00       ERR 5000.00      400.00        1.00      24.65        4.91
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PROFILE 5
  GEOPHONES      FROM:110                                      TO:220

        SHOT AT :220                                                   SHOT AT

NORTHING WESTING    ELEV.    CORR.                          CORR.
  (m)       (m)      (m)     ELEV.     DIST.     TIME      TIME       DIST.
 180.00   110.00   336.23    1.47      2.00     41.00     38.91       2.00
 180.00   120.00   335.95    1.19     10.00     38.00     36.32      10.00
 180.00   130.00   335.95    1.19     20.00     37.00     35.31      20.00
 180.00   140.00   335.73    0.97     30.00     36.50     35.13      30.00
 180.00   150.00   335.96    1.20     40.00     36.50     34.80      40.00
 180.00   160.00   335.51    0.75     50.00     34.00     32.94      50.00
 180.00   170.00   334.78    0.02     60.00     34.00     33.97      60.00
 180.00   180.00   334.76    0.00     70.00     31.00     31.00      70.00
 180.00   190.00   335.00    0.24     80.00     30.00     29.66      80.00
 180.00   200.00   335.27    0.51     90.00     29.00     28.28      90.00
 180.00   210.00   335.60    0.84    100.00     29.00     27.81     100.00
 180.00   220.00   336.27    1.51    110.00     30.00     27.86     110.00




  INCR.:10 metres



  CORR.               V(1)=700 ms/m                                           DEPT.
  TIME      T1(-)    V(1)      Vel.(2)    Vav.       COS(C)     T1(+)       (m)
  10.91     28.00   700.00   20000.00  5333.00      0.99       8.33       2.91
   9.32     27.00   700.00    4000.00  5333.00      0.99       4.14       1.45
  13.31     22.00   700.00    5714.29  5333.00      0.99       7.13       2.50
  16.63     18.50   700.00    5000.00  5333.00      0.99      10.25       3.59
  20.30     14.50   700.00   10000.00  5333.00      0.99      13.60       4.76
  20.44     12.50   700.00    5714.29  5333.00      0.99      11.88       4.16
  24.97      9.00   700.00    5714.29  5333.00      0.99      17.44       6.11
  25.50      5.50   700.00    4444.44  5333.00      0.99      15.00       5.25
  28.66      1.00   700.00    6666.67  5333.00      0.99      16.82       5.89
  30.28     -2.00   700.00    4000.00  5333.00      0.99      17.06       5.97
  34.81     -7.00   700.00   10000.00  5333.00      0.99      21.12       7.39
  36.86     -9.00   700.00        ERR  5333.00      0.99      23.22       8.13
```

PROFILE 6 NORTH BAY SEISMIC LINE 18

GEOPHONES FROM :140N TO :250N

| NORTHING (m) | WESTING (m) | ELEV. (m) | CORR. ELEV. | DIST. | TIME | CORR. TIME | DIST. |
|---|---|---|---|---|---|---|---|
| 140.00 | 180.00 | 335.73 | 0.97 | 110.00 | 46.00 | 44.40 | 2.00 |
| 150.00 | 180.00 | 335.96 | 1.20 | 100.00 | 42.00 | 40.02 | 12.00 |
| 160.00 | 180.00 | 335.51 | 0.75 | 90.00 | 41.00 | 39.76 | 20.00 |
| 170.00 | 180.00 | 334.78 | 0.02 | 80.00 | 38.00 | 37.97 | 30.00 |
| 180.00 | 180.00 | 334.76 | 0.00 | 70.00 | 35.00 | 35.00 | 40.00 |
| 190.00 | 180.00 | 335.00 | 0.24 | 60.00 | 33.00 | 32.60 | 50.00 |
| 200.00 | 180.00 | 335.27 | 0.51 | 50.00 | 31.50 | 30.66 | 60.00 |
| 210.00 | 180.00 | 335.60 | 0.84 | 40.00 | 31.00 | 29.61 | 70.00 |
| 220.00 | 180.00 | 335.79 | 1.03 | 30.00 | 29.00 | 27.30 | 80.00 |
| 230.00 | 180.00 | 335.87 | 1.11 | 20.00 | 27.00 | 25.17 | 90.00 |
| 240.00 | 180.00 | 336.50 | 1.74 | 12.00 | 22.00 | 19.12 | 100.00 |
| 250.00 | 180.00 | 336.75 | 1.99 | 2.00 | 10.00 | 6.71 | 110.00 |

V(1)=600 ms/m

| T(-) | V(1)=600 | Vel.(2) | AV.VEL. | COS(C) | T1(+) | DEPT. (m) |
|---|---|---|---|---|---|---|
| 23.00 | 600.00 | 4000.00 | 4348.00 | 0.99 | 21.23 | 6.33 |
| 18.00 | 600.00 | 5000.00 | 4348.00 | 0.99 | 17.53 | 5.21 |
| 13.00 | 600.00 | 5000.00 | 4348.00 | 0.99 | 22.02 | 6.54 |
| 9.00 | 600.00 | 6666.67 | 4348.00 | 0.99 | 22.43 | 6.67 |
| 5.00 | 600.00 | 8000.00 | 4348.00 | 0.99 | 20.50 | 6.09 |
| 2.00 | 600.00 | 4444.44 | 6896.00 | 1.00 | 18.71 | 5.59 |
| -0.50 | 600.00 | 5000.00 | 6896.00 | 1.00 | 17.31 | 5.17 |
| -5.00 | 600.00 | 5000.00 | 6896.00 | 1.00 | 19.72 | 5.89 |
| -9.00 | 600.00 | 2857.14 | 6896.00 | 1.00 | 19.10 | 5.71 |
| -13.00 | 600.00 | 1428.57 | 6896.00 | 1.00 | 18.83 | 5.63 |
| -20.00 | 600.00 | ERR | 6896.00 | 1.00 | 13.75 | 4.11 |
| -34.00 | 600.00 | ERR | 6896.00 | 1.00 | 2.92 | 0.87 |

```
PROFILE 7                                                          NORTH BAY SEISMI

 GEOPHONES               FROM : 255                           TO:420

NORTHING   WESTIN     ELEV.     CORR.                           CORR.
  (m)       (m)       (m)       ELEV.     DIST.      TIME      TIME      DIST.
  240.00   255.00   346.56     0.00      2.00     69.00     69.00      2.00
  240.00   270.00   346.55    -0.01     15.00     75.00     75.02     15.00
  240.00   285.00   346.10    -0.46     30.00     70.50     71.26     30.00
  240.00   300.00   345.62    -0.94     45.00     74.00     75.56     45.00
  240.00   315.00   345.74    -0.82     60.00     76.00     77.36     60.00
  240.00   330.00   345.92    -0.64     75.00     79.00     80.06     75.00
  240.00   345.00   346.12    -0.44     90.00     82.00     82.73     90.00
  240.00   360.00   346.29    -0.27    105.00     85.00     85.45    105.00
  240.00   375.00   346.30    -0.26    120.00     88.00     88.43    120.00
  240.00   390.00   346.30    -0.26    135.00     96.00     96.43    135.00
  240.00   405.00   346.31    -0.25    150.00    103.00    103.41    150.00
  240.00   420.00   346.32    -0.24    165.00    106.00    106.40    165.00
                                                                ERR




                                        V1=600 ms/m
   CORR.   Vel(1)                      Vel(2)                                              DEPT.
   TIME     ms/m       T1(-)           ms/m        Vav.          COS(C)      T1(+)      (m)
  104.00   600.00    -35.00         4285.71     5000.00           0.99      67.50         20
  103.02   600.00    -28.00         8571.43     5000.00           0.99      72.53         22
  102.76   600.00    -31.50         4000.00     5000.00           0.99      68.52         20
   99.56   600.00    -24.00         3750.00     5000.00           0.99      69.61         21
   93.36   600.00    -16.00         7500.00     5000.00           0.99      65.21         19
   92.06   600.00    -12.00         3750.00     5000.00           0.99      66.62         20
   86.73   600.00     -4.00         7500.00     5000.00           0.99      63.96         19
   85.45   600.00      0.00        10000.00     5000.00           0.99      65.39         19
   85.43   600.00      3.00         3750.00     6000.00           0.99      68.36         20
   85.43   600.00     11.00         5000.00     6000.00           0.99      76.36         23
   86.41   600.00     17.00        10000.00     6000.00           0.99      84.33         25
   86.40   600.00     20.00             ERR     6000.00           0.99      87.29         26
                                                                              ERR        ERR
```

```
PROFILE 8

 GEOPHONES                  FROM:240                     TO:405

NORTHING     WESTING      ELEV.        CORR.                          CORR.
  (m)          (m)         (m)         ELEV.      DIST.      TIME     TIME
  180.00       240.00      344.66     -1.90        2.00      64.00    67.77
  180.00       255.00      345.83     -0.73       15.00      67.00    68.45
  180.00       270.00      347.19      0.63       30.00      80.00    78.75
  180.00       285.00      346.80      0.24       45.00      75.00    74.52
  180.00       300.00      346.27     -0.29       60.00      81.00    81.53
  180.00       315.00      346.29     -0.27       75.00      82.00    82.54
  180.00       330.00      346.32     -0.24       90.00      86.00    86.48
  180.00       345.00      346.28     -0.28      105.00      91.00    91.56
  180.00       360.00      346.25     -0.31      120.00      92.00    92.62
  180.00       375.00      346.28     -0.28      135.00      91.00    91.56
  180.00       390.00      346.31     -0.25      150.00      93.00    93.50
  180.00       405.00      346.40     -0.16      165.00      97.00    97.32
  180.00




                       CORR.                 Vel(2)                             DEPT.
 DIST.      TIME       TIME       T1(-)      ms/m          COS(c)      T1(+)     (m)
   2.00     97.50     101.28     -33.50     4615.38        1.00       71.57     17.89
  15.00     94.00      95.45     -27.00     4285.71        1.00       66.41     16.60
  30.00    100.00      98.75     -20.00    20000.00        1.00       73.93     20.00
  45.00     93.00      93.02     -18.50     2857.14        1.00       70.04     17.51
  60.00     89.00      89.58      -8.00    10000.00        1.00       73.66     18.41
  75.00     87.00      87.54      -5.00     6666.67        1.00       72.56     18.14
  90.00     86.00      86.98      -0.50     4285.71        1.00       75.96     18.99
 105.00     84.00      85.06       6.50     4615.38        1.00       79.12     19.78
 120.00     79.00      80.12      13.00    20000.00        1.00       75.73     18.93
 135.00     77.00      77.56      14.50    10000.00        1.00       72.12     18.03
 150.00     75.00      76.00      17.50     2307.69        1.00       72.00     18.00
 165.00     67.00      67.32      30.50        0.00        1.00       67.64     16.91
```

```
PROFILE 9                          NORTH BAY SEISMIC
GEOPHONES                         FROM:105                   TO:270


 NORTHIN   WESTING     ELEV.                          CORR.
   (m)       (m)       (m)      DIST.     TIME      TIME      DIST.     TIME
  105.00    280.00     0.00      2.00     0.00     75.00      2.00      0.00
  120.00    300.00     0.00     15.00    36.00     79.00     15.00     37.00
  135.00    315.00     0.00     30.00    69.00     79.50     30.00     63.00
  150.00    325.00     0.00     45.00    78.50     81.00     45.00     72.00
  165.00    340.00     0.00     60.00    82.50     85.00     60.00     77.00
  180.00    355.00     0.00     75.00    85.00     88.00     75.00     80.00
  195.00    370.00     0.00     90.00    86.00     89.00     90.00     85.00
  210.00    385.00     0.00    105.00    86.00     90.00    105.00     88.50
  225.00    400.00     0.00    120.00    89.00     91.00    120.00     91.00
  240.00    415.00     0.00    135.00    91.00     93.00    135.00     92.00
  255.00    430.00     0.00    150.00    94.00     95.00    150.00     94.00
  270.00    445.00     0.00    165.00    95.00     97.00    165.00     98.00




                                                                INCR.:15


          Vel(1)=700 ms/m
                                                                      DEPT.
  T1(-)    VEL.(1)    VEL.(2)     AV.VEL.       COS(0)     T1(+)      (m)
 -22.00    700.00    3750.00     6666.00         0.99     74.50     25.93
 -14.00    700.00   12000.00     6666.00         0.99     74.50     25.93
 -11.50    700.00   12000.00     6666.00         0.99     73.00     25.41
  -9.00    700.00    4285.71     6666.00         0.99     73.50     25.58
  -2.00    700.00    5000.00     6666.00         0.99     74.50     25.93
   4.00    700.00    5000.00     6666.00         0.99     74.50     25.93
  10.00    700.00    7500.00     6666.00         0.99     70.50     24.54
  14.00    700.00    5000.00     6666.00         0.99     68.50     23.84
  20.00    700.00    4285.71     6666.00         0.99     64.50     22.45
  27.00    700.00    2000.00     6666.00         0.99     61.50     21.41
  42.00    700.00     545.45     6666.00         0.99     50.50     17.58
  97.00    700.00        ERR     6666.00         0.99     48.50     16.88
                                                             ERR       ERR
```

```
PROFILE 10                     NORTH BAY SEISMIC                    ALONG ROA

GEOPHONES              FROM:110                            TO:275

 NORTHIN    WESTI     ELEV.                          CORR.
   (m)       (m)       (m)       DIST.      TIME     TIMT       DIST.     TIME
  275.00   300.00     0.00       2.00       0.00     74.00       2.00      0.00
  260.00   295.00     0.00      15.00      36.50     72.00      15.00     33.50
  245.00   295.00     0.00      30.00      67.00     76.00      30.00     60.50
  230.00   295.00     0.00      45.00      75.50     79.00      45.00     83.00
  215.00   290.00     0.00      60.00      78.50     80.00      60.00     86.00
  200.00   290.00     0.00      75.00      82.00     84.00      75.00     89.50
  185.00   290.00     0.00      90.00      85.50     86.50      90.00     93.00
  170.00   290.00     0.00     105.00      88.50     87.00     105.00     93.00
  155.00   280.00     0.00     120.00      90.00     91.00     120.00     94.50
  140.00   280.00     0.00     135.00      91.50     91.00     135.00     96.50
  125.00   280.00     0.00     150.00      93.00     92.50     150.00     98.50
  110.00   270.00     0.00     165.00      95.00     95.00     165.00     99.00
```

```
                   Vel(1)=650 ms/m
CORR.                                                                    DEPT.
TIME     T1(-)    Vel(1)     Vel.(2)    Vav.         COS(C)     T1(+)     (m)
97.00   -23.00    650.00   30000.00  5625.00          0.99      76.00    24.87
96.00   -24.00    650.00    6000.00  5625.00          0.99      73.00    23.89
95.00   -19.00    650.00    6000.00  5625.00          0.99      76.00    24.87
93.00   -14.00    650.00    6000.00  5625.00          0.99      77.00    25.19
89.00    -9.00    650.00    5454.55  5625.00          0.99      74.00    24.21
87.50    -3.50    650.00    5000.00  5625.00          0.99      76.50    25.03
84.00     2.50    650.00    8571.43  6666.00          1.00      75.50    24.65
81.00     6.00    650.00    4285.71  6666.00          1.00      73.00    23.84
78.00    13.00    650.00   15000.00  6666.00          1.00      74.00    24.17
76.00    15.00    650.00    4615.38  6666.00          1.00      72.00    23.51
71.00    21.50    650.00    4615.38  6666.00          1.00      68.50    22.37
67.00    28.00    650.00        ERR  6666.00          1.00      67.00    21.86
```

## Appendix C

## TRICIL SITE

C-1: Johnson et al. (1986)

J-1.

C -1

# DIFFUSIVE CONTAMINANT TRANSPORT IN NATURAL CLAY: A FIELD EXAMPLE AND IMPLICATIONS FOR CLAY-LINED WASTE DISPOSAL SITES

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## ABSTRACT

Vertical core samples were obtained from holes drilled into an impervious, unweathered water-saturated clay deposit beneath a five-year old hazardous waste disposal cell at a site in southwestern Ontario. After sectioning the cores, pore water obtained by squeezing numerous core segments was analyzed for chloride and volatile organic compounds. Waste-derived chloride was detected in the clay to a maximum depth of 83 cm below the bottom of the cell. The most mobile organic compounds were found only to a depth of ~15 cm. Although a distinct downward hydraulic gradient existed in the clay because of the high water table in the waste, the vertical chemical profiles in the clay were the result of molecular diffusion. The smaller distances of penetration for the organic compounds relative to chloride are attributed primarily to adsorption. Because the clay deposit at the site is 25 m thick, it will take thousands of years for contaminants to diffuse through the clay into the underlying aquifer. This study has implications with respect to low-permeability clay liners used at waste disposal sites. For liners of typical thickness (~1 m) molecular diffusion will cause breakthrough of relatively mobile contaminants in less than 5 years, and the flux of contaminants out of such liners may be significant.

## INTRODUCTION

The use of clay liners at waste disposal sites is frequently advocated as a means of minimizing the potential for groundwater contamination. It is commonly thought that if the hydraulic conductivity (K) of the clay is low and if there are no structural defects, then the liner will provide a barrier between the waste and the underlying hydrogeologic domain. Guidelines for the properties of clay liners commonly specify that they should have a K less than $1 \times 10^{-7}$ cm/s so that the rate of advective transport will be small. Even when advection is minimal, however, contaminants can migrate through the clay at rates that may be significant. This non-advective migration is caused by molecular diffusion.

A field investigation of contaminant migration in a natural clay deposit beneath a completed cell at a hazardous waste disposal site is described here. The clay is unweathered, uniform, and has a very low K ($< 5 \times 10^{-8}$ cm/s). It thus has all of the features normally desired of a clay liner. Contaminant profiles with depth were measured in pore water extracted from core samples of the clay underlying the site. The goals of the investigation were to determine the rates at which inorganic and organic compounds from the waste migrate downward through the clay and to assess the applicability of simple diffusion models for predicting these rates.

## SITE SETTING AND PREVIOUS STUDIES

The waste disposal facility, operated by Tricil Limited, is located 15 km southwest of Sarnia, Ontario (Figure 1). The site was selected for this study primarily because the natural clay deposit is 25 m thick and therefore vertical boreholes through the waste could be drilled a meter or two into the underlying clay without destroying the integrity of the overall deposit. The site possesses additional positive attributes, such as waste material that offers no obstructions to drilling, accurate information on the locations and depths of the cells, and hydrogeological conditions that have been determined in detail in previous investigations. The waste-disposal cell selected for this investigation was excavated in 1979, and received its final load of waste in 1980. The waste mass consisted of flyash from a nearby coal-fired electrical generating station to which the liquid hazardous wastes were mixed prior to disposal. The cell is approximately 15 m deep, with a 2 m thick cover of compacted clay.

The study site is situated in the St. Clair clay plain, which extends more than 20 km in all directions from the site (Figure 1). The clay deposit which is late Quaternary in age, was formed by glaciers that protruded into a large glacial lake. The deposit contains numerous granules of shale bedrock indicative of the glacial-till origin of the deposit. About 40% of this glacial till is clay-sized particles, which are primarily illite and chlorite (Quigley and Ogunbadejo, 1). The remainder consists of silt and sand-sized material and a small percent of pebbles.

Desaulniers (2), and Desaulniers et al. (3,4) have studied the permeability of the clay, and the flow rates and age of groundwater in the clay at several locations on the clay plain including the site described here. These investigators concluded that, below about 5 m from ground surface, the clay is unweathered, and has an average K less than $5 \times 10^{-8}$ cm/s. Groundwater flow is downward at an average linear velocity less than several millimeters per year. Isotopic dating studies of the groundwater in the unweathered clay indicated that it is generally many thousands of years old. Desaulniers and co-workers also concluded that natural solutes in the groundwater, such as Cl$^-$ and $^{18}O$ have developed vertical concentration profiles up from the underlying bedrock due largely to molecular diffusion since the retreat of the Pleistocene glaciers. Desaulniers et al. (4) successfully simulated the vertical concentration profiles by means of one-dimensional diffusion models and diffusion times of 12,000 to 16,000 years.

Goodall and Quigley (5) and Crooks and Quigley (6) determined vertical profiles of several inorganic, leachate-derived constituents by the analysis of core samples taken from weathered clay at the bottom of shallow pits at a nearby municipal landfill in Sarnia. While the data suggested diffusion as the dominant cause of profile development, they only had limited success in the fitting of a diffusion model to the data. This was in part due to advective transport in fractures in the weathered zone. The current investigation has some similarities to the work of Quigley and co-workers, but differs in that it examines the clay at greater depth where it is unweathered, and in that it includes organic contaminants.

## EXPERIMENTAL

### Sample Collection and Preparation

Samples from three boreholes located approximately 5 m apart in one 5-year old cell were collected using a Central Mine Equipment (CME Model 75) drill rig with continuous flight, 1.6 m (5 foot) long hollow-stem augers. Beginning approximately 0.5 m above the bottom of the cell, cores were taken with a 1.6 m (5 foot) split spoon tube sampler. In this manner, samples were collected from the bottom of the flyash and into the underlying clay to a depth of approximately 2 m below the interface. As the samples were brought to the surface, they were removed from the split-spoon sampler and lightly washed with water to remove most of the external contamination.

Immediately after sampling, the cores were taken to an on-site laboratory and placed in a fume hood for further sample preparation. The interface between the flyash and clay was easily located because of its abruptness. Moving both directions from the interface the core was cut into either 3.8 or 7.6 cm (1.5 or 3 inch) sections with a sharp knife. The contamination on the exterior of each section was then carefully cut away with two frequently-cleaned knives. Each section was wrapped in aluminum foil which had previously been heated at 450°C for one hour. Each core section was then placed in a 500 mL amber jar whose cap was lined with aluminum foil. Both the jar and the foil had been heated at 450°C. The samples were then stored at 4°C.

Pore water was removed from the core sections by compressing the sections in specially designed consolidometers (Figure 2). These devices, which were similar in design to those described by Patterson et al. (7), were capped cylinders which contained a moveable piston. Pressure was exerted on the sample by the piston, which was driven by compressed nitrogen. Samples were typically pressed to 600 psi (42 kg/cm$^2$). The piston area was 44 cm$^2$, thus a total force of approximately 2000 kg was exerted on the sample. In the bottom of each consolidometer were a series of glass-fiber filters (Gelman Inc., Ann Arbor, MI) and screens (100 mesh stainless steel) and a 1/16 inch o.d. tube which carried the pore water to a 10 mL syringe. The syringe was fitted with a small teflon valve (Mininert, Pierce Chemical, Rockford, IL) to facilitate removal of the syringe from the consolidometer. In order to minimize both volatilization from the syringe and the pressure within the syringe, the plunger was replaced with a teflon cap which was machined to fit inside the barrel of the syringe. The cap floated on top of the liquid as the syringe filled (surface tension prevented the water from creeping around the cap). At the completion of squeezing, the valve on the syringe was closed, and the syringe was removed. A teflon-tipped plunger was placed into the top of the syringe, the valve opened, and the liquid transferred to two sample bottles. The first bottle (1.5 mL pre-cleaned amber glass) was carefully filled to minimize volatilization; no significant headspace remained. This bottle was capped with a teflon lined septum and stored for organics analysis. The remainder of the sample was then placed in a 25 mL amber glass bottle and saved for inorganics analysis. Both sample bottles were stored at 4°C until analyzed. Pore-water extraction was carried out at 10°C to ensure that concentrations in the extracted pore water were the same as in the undisturbed clay.

The portions of the consolidometer which came into contact with the sample were made of 304 stainless, glass or teflon. A set of 9 consolidometers was used. Between uses the consolidometers were disassembled, washed with soap and water and acetone and heated for at least 6 hours at 250°C.

## Chloride Analysis

Chloride analyses were performed using ion chromatography. In addition to the regular sample analyses, approximately 15% of the samples were resubmitted as blind duplicates. Synthetic samples, spiked samples and serially diluted samples were also submitted for quality assurance. Accuracy and precision were excellent on all samples. Extracts from one core (No. 1) were analyzed for major cations and trace metals and those results will be reported elsewhere.

## Organics and Total Organic Carbon (TOC) Analysis

Volatile organic compound analyses were carried out by purge and trap with whole column cyrotrapping (P&T/WCC) on a gas chromatograph/mass spectrometer/data system (GC/MS/DS) as described by Pankow and Rosen(8). Briefly, an aliquot of a sample was first diluted with organic-free water to 5.0 mL in the purge vessel of the P&T unit. The volume of the aliquot varied between 0.030 mL and 1.0 mL, and depended on the expected concentration. The aliquot size was 1.0 mL for samples relatively far away from the interface, and was decreased as the interface was approached. An undiluted 5.0 mL sample could not be run for the low-level samples since 5.0 mL of sample was not available for these determinations. After dilution, 10 uL of a P&T internal standard (IS) solution in methanol was added to the purge vessel. The IS solution contained 7.7 ng/uL each of bromochloromethane, 1-chloro-2-bromopropane, and 1,4-dichlorobutane. Each sample was then analyzed by P&T/WCC using a Chrompack CP-Sil8 CB 1 um film thickness capillary column (Chrompack, Inc., Raritan, NJ). Quantitation was achieved based on the responses of the characteristic ions of the target analyte compounds and the IS compounds. TOC analyses were performed on one core (No. 1) by oxidation by ultra-violet light and infrared detection using a Dohrmann DC-80 analyzer (Envirotech, Corp. Mountain View, CA).

## Water Content and Porosity

The water content and porosity of sections of one of the cores (No. 3) were estimated by drying and weighing portions of the core. A known mass of core section was placed into a pre-tared vial and dried at 105°C for 12 hours. The vial and soil were re-weighed and the weight loss attributed to water loss. Water content (WC) was estimated as the mass of water lost (W) divided by the total mass of the water and soil (W+S). Porosity (n) of the core sections was estimated using 2.7 g $cm^{-2}$ as the soil particle density of the clay.

## Soil Organic Carbon Content

The soil organic carbon contents, expressed as a fraction ($0 \leq SOC \leq 1$), were determined for each section of core which contained a significant amount of the target organic compounds. A combustion method was used (Johnson, (9); Johnson et al. (10)). Steps in the analysis procedure included: 1) the samples of the clay were dried at 80°C to constant weight; 2) the samples were acidified with 5% $SnCl_2$ in 3 N HCl and dried at 50°C; 3) a known mass of sample was placed in a pre-cleaned copper combustion boat; 4) a batch of 12 samples and standards were placed in a sample carousel; 5) each sample was dropped into a combustion oven at 700°C; 6) carrier gas (90% He/10% $O_2$) swept the $CO_2$ evolved from the sample into a methanator where it was quantitatively converted to methane; and 7) the methane was detected with a flame ionization detector. All samples were analyzed at least in duplicate and the results averaged.

Two methods of calibration were used; combustion of known volumes of standard solutions of organic compounds (e.g. sugars), and analysis of "standard soils". The standard soils spanned a range of SOC contents (0.11-4.0% SOC as carbon), and had been analyzed previously by several laboratories (Hassett, (11)). These soils were prepared and analyzed in the same manner as the samples. Excellent agreement between the two types of standards was obtained.

## Batch Sorption Experiments

Sorption experiments were conducted using uncontaminated soil from the site. The soil was dried to constant weight at 80°C. 10 g quantities of soil were then placed in 40 mL vials, to which 25 mL of water, containing the compounds of interest was added. The vials were equilibrated for 24 hours by tumbling end-over-end at 30 revolutions per minute. Water concentrations were analyzed by headspace GC, calibrated using standard solutions.

## RESULTS AND DISCUSSION

Chloride concentrations for three cores are presented in Table I. The samples of flyash from just above the clay interface in each core were analyzed and their concentrations taken as the concentrations at the interface. Concentrations in the core sections were normalized to these values and are also reported in Table I. In each of the cores the $Cl^-$ content was high in the flyash and decreased downward in the clay. Background $Cl^-$ values in the clay were approximately a factor of ten lower than the flyash values and were calculated from the average $Cl^-$ concentrations in the core sections at depths greater than the penetration depths of the flyash-derived $Cl^-$. Background $Cl^-$ in the clay originated in the bedrock shale beneath the clay. The maximum distances from the interface that flyash-derived $Cl^-$ could be distinguished from background were 83 cm in core 1, 75 cm in core 2, and 46 cm in core 3. The profiles with depth for the cores are presented in semi-log format in Figures 3-5.

The $Cl^-$ concentrations for core 1 exhibit a classic diffusion profile (Figure 6). The $Cl^-$ profile from core 2 shows a reversal in concentration gradient in the middle of the profile but follows the diffusion shape in the lower portion. Core 3 follows the expected diffusion profile in the sections just below the interface, but then drops sharply to lower values. The reversal in core 2 and the differences in depth of penetration of $Cl^-$ in the three cores suggest that the $Cl^-$ concentrations in the flyash at the interface varied in time. Even when spatial and temporal $Cl^-$ variations in the flyash at the bottom of the pit are considered possible, however, the reversal in core 2 is difficult to explain because its position in the core indicates that conditions changed more than a year after the pit was filled and capped.

The shallow $Cl^-$ profile observed in core 3 may have resulted from depth-dependent effective diffusion coefficients due to heterogeneities in the clay. To evaluate this hypothesis, the porosities of the core 3 sections were estimated from the water content data (Table I). They are similar to the values (35 - 40%) reported for the clay by Hydrology Consultants Limited (12). The porosity of the section nearest the interface (i.e. the 0.0-3.8 cm section) was somewhat lower than those farther into the clay. In fact no pore water was recoverable by compression from this section. This may have been the result of compaction or dehydration during the excavation of the cell. The lower porosity of the clay nearest the interface in core 3 would be expected to cause some restriction in the rate of contaminant migration in the clay. This may account in some degree for the fact that $Cl^-$ migrated a smaller distance in this core. Comparisons with the other cores in this context cannot be made because the water contents of the other cores were not determined.

Organics analysis data for the three cores are given in Table II. Also, as with the $Cl^-$ data, the core concentrations were normalized to the concentrations in the flyash just above the interface. Normalized data for the organics are plotted versus depth in Figures 3-6. The organic compounds were detected a maximum distance of 15 cm below the interface. The dominant organic compounds, such as benzene, toluene, and ethylbenzene, had concentrations of many hundreds to several thousand ug/L in the flyash at the interface. The limits of detection for these compounds in the clay were on the order of 1 ug/L or less. The fact that they were not found, even at very low concentrations, at a distance of greater than ~15 cm indicates that there was a relatively abrupt migration front. Comparison of the maximum migration distance of $Cl^-$ (83 cm) with the maximum distances for the organic compounds indicates that the organics have been retarded relative to $Cl^-$. As discussed below, batch sorption and SOC values have indicated that sorption played an important role in retardation.

The TOC profile for the core 1 pore water extends significantly deeper than any of the organic compounds identified by the P&T analysis procedure. Additionally, the sum of the concentrations of the target compounds represents less than one percent of the TOC concentrations. The bulk of the TOC is probably made up of water-miscible compounds, including acetone, methyl ethyl- and methyl isobutyl ketone (Nesbitt, (13)). These compounds sorb only slightly and would, therefore, be expected to diffuse 3-20 times faster than the target organics. Figure 6 suggests that this is the case.

SOC analyses indicate that the clay contains 0.7-1.3% by weight as carbon (average = 1.1%, Table II). Batch sorption experiments using trichloroethene, benzene, toluene, and ethylbenzene in the aqueous concentration range 100-25,000 ug/L result in a highly non-linear sorption isotherm. Partition coefficient ($K_d$) values at low concentrations are significantly higher than the partition coefficient values calculated using the relationship:

$$K_{d,calc} = K_{oc} \times SOC \qquad (1)$$

where $K_{oc}$ is the organic carbon partition constant and SOC is the soil organic carbon content (Table III). This "excess sorption" at low concentrations may be due to non-hydrophobic interactions between the organics and the clay (14). This possibility, and its effect on diffusion are currently being investigated and will be reported on elsewhere. The $K_d$ values reported in Table III are those determined in batch tests where the final concentrations in the water were ~1000 ug/L.

The hydraulic conductivity of the clay was measured by Hydrology Consultants (12) using piezometer tests in the field and by permeameter tests of core samples in the laboratory. Values of K were in the range of $10^{-8}$ to $10^{-9}$ cm/s, with a geometric mean value of $6 \times 10^{-9}$ cm/s. The water table in the waste cell was close to the level of the original ground surface (i.e. it is below the cap). The average level of the potentiometric surface in the bedrock just below the clay was about 7 m below ground surface. A 7 m average difference in hydraulic head therefore acted across the 25 m thickness of clay beneath the pit. Using Darcy's law with a porosity (n) = 0.37, a downward velocity of 0.15 cm/year is predicted. Even if the downward hydraulic gradient across the clay existed from the date of burial of the wastes, and if the only process causing downward $Cl^-$ migration was advection, then the penetration distance would be only 0.75 cm. The observed penetration distances for $Cl^-$ in the three cores (83, 75 and 46 cm) indicate that this advection distance is insignificant in comparison to expected and observed diffusion distances. It is concluded, therefore, that advective flow is not a major influence on $Cl^-$ migration. This conclusion is similar to that arrived by Desaulniers et al.(4) in their investigation of bedrock-derived $Cl^-$ and isotopes in the clay in the Sarnia area. A similar conclusion is reached for advection of the organics at the Tricil site. Even with their retardation due to sorption, diffusion distances for the organics will be much larger than those resulting from advection.

## MODELING

The minor role of advection and the relatively homogeneous nature of the clay make it appropriate to simulate the downward migration of $Cl^-$ and the organic compounds by means of diffusion models based on Fick's second law:

$$dC/dt = D_{e,c}\partial^2C/\partial z^2 \qquad (2)$$

where z is the vertical direction and $D_{e,c}$ is the effective solute diffusion coefficient in the clay.

Materials diffusing into the clay must first diffuse through the flyash to the interface. Assuming that the contaminant concentrations in the flyash are initially uniform, and that the initial concentrations of the contaminants in the clay are zero, a concentration gradient will form in the flyash near the interface. If the effective diffusion coefficient in the flyash ($D_{e,f}$) is greater than $D_{e,c}$, then the concentration at the interface will stabilize at a value determined by the initial concentration in the flyash and the relative values of the two effective diffusion coefficients. Furthermore, if $D_{e,f} > D_{e,c}$, then concentration profiles in the clay, when normalized to the concentration at the interface will be independent of $D_{e,f}$ and only a function of $D_{e,c}$. Since $D_{e,f}$ is almost certainly greater than $D_{e,c}$ (because the flyash is a much less compact and cohesive material than the clay), the solution to eq 2 is (Crank (15)):

$$C/C_o = \text{erfc}\ [(z/D_{e,c}t)^{1/2}] \qquad (3)$$

where $C_o$ = the concentration at the interface.

The diffusion profile for $Cl^-$ in core 1 and simulated profiles based on eq 3 are shown in Figure 6. The solid line represents the measured concentrations in the core sections. The dashed lines are model profiles using a time of 1800 days and $D_{e,c}$ values as indicated. The data for $Cl^-$ display a close match between the observed concentrations and the simulated profile for $D_{e,c} = 4\text{-}6 \times 10^{-6}$ $cm^2/s$. This range is quite similar to values observed in the laboratory by Desaulniers (2) and by Crooks and Quigley (6). For core 2, a $D_{e,c} = 4 \times 10^{-6}$ $cm^2/s$ produces a good match to the lower portions of the observed $Cl^-$ profile. In the portion of core 2 closest to the interface, however, the $Cl^-$ concentrations are much lower than expected, and the profile is fit best with $D_{e,c} = 8 \times 10^{-7}$ $cm^2/s$.

For core 3 the penetration distance for the $Cl^-$ is much smaller than for the other two cores, and the profile cannot be fitted closely by a single simulation. The portion of the profile closest to the interface is best fit by $D_{e,c} = 2 \times 10^{-6}$ $cm^2/s$. The lower portion of the core is best simulated by $D_{e,c} = 3 \times 10^{-7}$ $cm^2/s$. The latter value is much smaller than those determined in the laboratory studies. This suggests that the initial concentration distribution of $Cl^-$ in the flyash may have changed with time. The possible effects of a non-constant interface concentration on the diffusion profiles have been evaluated. Using a constant $D_{e,c} = 4 \times 10^{-6}$ $cm^2/s$, but varying the concentration at the interface in time, an attempt was made to duplicate the observed profiles in cores 2 and 3. This was not successful, and the reasons for the variations from ideal diffusion behavior remain unclear.

$D_{e,c}$ in the soil is less than the free-solution diffusion coefficient (D) at the corresponding temperature due to the tortuous path which the molecules must follow through the porous media. This relationship is frequently expressed as:

$$D_{e,c} = D * \tau \tag{4}$$

where $\tau$ is a correction factor ($0.0<T<1.0$) to account for tortuosity and porosity effects.

Values of $\tau$ for the clay can be estimated using eq 3 from the observed $D_{e,c}$ values for $Cl^-$ and the literature value of D at a corresponding temperature (10°C). For $D = 1.5 \times 10^{-5}$ $cm^2/s$ (Li and Gregory, (16)), and $D_{e,c} = 4\text{-}6 \times 10^{-6}$ $cm^2/s$, T is in the range 0.20-0.33.

The diffusion model can also used to simulate profiles of the organic compounds in the clay (Figure 6). In this case, not only the effects of tortousity and porosity must be taken into account, but also the effects of molecular size and sorption.

The effect of molecular size on the diffusion coefficient can be estimated for the compounds using literature data. For example, D values have been measured for a variety of organics in dilute aqueous solution by Bonoli and Witherspoon (17). They suggest that values of D in the range $5\text{-}9 \times 10^{-6}$ $cm^2/s$ are appropriate for benzene, toluene, and several cycloalkanes at 25°C. D values for other compounds can be estimated from their data using an approximation equation for the diffusion coefficient which takes into account the effect of molecular size (Wilke and Chang, (18)):

$$D_1/D_2 = \left|\frac{MW_2/r_2}{MW_1/r_1}\right|^{0.6} \tag{5}$$

where $D_1$ and $D_2$ are the free solution diffusion coefficients of a pair of organic compounds of interest at the temperature of interest, $MW_1$ and $MW_2$ are their molecular weights and $r_1$ and $r_2$ are the densities of the compounds at their boiling points. The latter are generally not known. Substitution of densities at a standard temperature generally provide relative diffusion coefficients within 10% of experimental values.

Diffusion coefficient values (measured or calculated) for the compounds of interest are found in Table III. The values observed for the organics in the field cores are much smaller than would be predicted from the product of D and tortuosity values. This suggests that the primary reason for the observed differences in diffusion coefficient values of $Cl^-$ and the organics is the sorption of the organics on the clay.

The effect of sorption on diffusion profiles can be modeled by substituting $D'_{e,c} = D_{e,c}/R$ for $D_{e,c}$ in eqs 2 and 3. R is the retardation factor:

$$R = 1 + \rho_b K_d / n \quad (6)$$

where $\rho_b$ = soil bulk density ($g/cm^3$)

and n = soil porosity.

$K_d$ may be determined in laboratory tests, or estimated based on eq 1. Both approaches have been employed here and the results are tabulated in Table III.

The combination of sorption and molecular weight effects leads to estimated total reductions in diffusion coefficient values relative to chloride of from 5 to 50. The $D'_{e,c}$ values estimated using the batch sorption test data are closer to the observed $D'_{e,c}$ values than are those based on eq 1.

## FUTURE DOWNWARD MOVEMENT OF THE CONTAMINANTS AT THE SITE

The diffusion model was used to predict the future downward diffusion of the contaminants. For $Cl^-$ a $D_{e,c}$ of $4 \times 10^{-6}$ $cm^2/s$ was used to simulate migration of $Cl^-$ through the 25 m thick deposit of clay beneath the cell (Figure 7a) for periods of up to 10,000 years. These simulations suggest that flyash-derived $Cl^-$ will begin to arrive in the bedrock at detectable levels ($C/C_o = 0.01$) in about 3,000 years. A steady-state flux of $Cl^-$ to the aquifer will be achieved in about 10,000 years.

These predictions, and those which follow, assume that the contaminant concentrations beneath the clay are maintained at near zero values as the result of groundwater in the bedrock sweeping past the bottom of the clay. They also assume that the mass of contaminants in the flyash is not significantly depleted during the simulation. Because the clay is 25 m thick while the flyash is 15 m thick, and because the $Cl^-$ concentration in the flyash is below its saturation concentration, it is expected that depletion will effect the development of the $Cl^-$ profiles in the clay after a few thousand years, resulting in shallower than predicted profiles.

Predicted diffusion profiles for organic compounds using $D'_{e,c}$ values of $2 \times 10^{-7}$ and $2 \times 10^{-8}$ $cm^2/s$ are also given in Figure 7a. The largest value represents the rapidly migrating organics, such as benzene in core 1. The smaller value is representative of the more retarded organic compounds identified in the waste. Breakthrough of organics should be defined on the basis of a lower $C/C_o$ than for $Cl^-$ (e.g. 0.001) because the organic compounds are often of concern at very low concentrations. For example, if benzene exists in solution at 100 ppm at the top of the liner, a $C/C_o = 0.001$ still corresponds to a concentration of 100 ppb, which is high relative to the levels that should be achieved in drinking water. Thus, in the diffusion modeling, breakthrough of the organics will be specified as occurring at a simulated $C/C_o = 0.001$. When defined in this manner, periods of 5,000 to 15,000 years are required for breakthrough to occur. For the compounds which resist degradation, their steady-state diffusion profiles will only be reached on a geologic time scale. Thus, even though a $C/C_o = 0.001$ may represent a significant concentration, the thick clay deposits at the study site will prevent diffusive transfer to the aquifer for a long period of time. In addition to ensuring a long breakthrough time, the thickness of the deposit also results in a gradual concentration gradient within the clay. This means that, even after breakthrough occurs, the diffusive flux out of the clay will be small.

## IMPLICATIONS FOR HAZARDOUS WASTE DISPOSAL AT SITES WITH CLAY LINERS

The thick clay deposit beneath the study site is exceptional in a waste-disposal context. It is becoming increasingly common for hazardous waste cells to be lined with compacted clay of ~ 1 m thickness as a means of isolating the waste from the underlying hydrogeologic domain. The field results obtained in this study can be used, however, to develop predictions regarding diffusive contaminant migration through man-made clay liners.

Figure 7b, produced using the diffusion model described above, indicates that, for a 1 m thick liner, $Cl^-$ will reach a breakthrough concentration of $C/C_o = 0.01$ in approximately 4 years ($D_{e,c} = 4 \times 10^{-6}$ cm$^2$/s). The diffusive mass flux into the hydrogeologic domain beneath the liner will attain 10% of the eventual steady state value in about 5 years, and reach steady-state in approximately 40 years. Mobile organic compounds such as benzene will be retarded relative to chloride, but it is again appropriate to calculate breakthrough times for the organics based on $C/C_o$ values of 0.001. When the effective diffusion coefficient for benzene obtained in this study ($2 \times 10^{-7}$ cm$^2$/s) is used to calculate a breakthrough time for a 1 m thick liner, 6 years is obtained. There are many other organic compounds which are as mobile as benzene. Thus, diffusion-controlled breakthrough of the least retarded organic compounds may occur in five years or less. Steady-state conditions will be approached in less than 100 years. For a 1 m thick liner, the concentrations in the waste may be only slightly depleted, and steady-state losses may be substantial.

To obtain an indication of the mass of contaminants which may diffuse through a liner at steady state, consider a 1 m thick liner with an area of 100 x 100 m. Once steady state has been achieved, flux out of the liner is described by Fick's first law:

$$\text{Flux} = n\, D_{e,c} \frac{dc}{dz} \qquad (7)$$

$D_{e,c}$ is used, rather than $D'_{e,c}$, because at steady state, adsorption equals desorption and there is no net retardation for any species. If the contaminant has a concentration of 1 g/L in the waste at the top of the liner, if $D_{e,c}$ is $1.5 \times 10^{-6}$ cm$^2$/s, $n = 0.4$, and if the ground water flow maintains the concentration beneath the liner at a small fraction (e.g. 0.01) of the concentration in the waste, then the steady-state mass transport rate through the liner will be approximately 19 kg/year (1.9 g/m$^2$/year). For some compounds an annual release of this magnitude would cause a major adverse impact on groundwater quality. For example, 19 kg of benzene has the potential to contaminate 3.8 billion liters of water at the EPA-suggested drinking water limit of 0.005 mg/L.

All of the breakthrough times and the fluxes mentioned above are based on the assumption that advection through the liner is insignificant. In many situations hydraulic gradients across liners are large (i.e. > 1) and therefore average linear velocities across the liners may in fact be significant. For conditions in which the average linear velocity is greater than a few centimeters per year, breakthrough times and mass transfer rates should be calculated using models that include both advection and diffusion, such as those described by Desaulniers et al. (2), Rowe and Booker (19), and Gray and Weber (20). The diffusion analysis presented above, however, thus represents a best-case analysis in that it provides maximum breakthrough times and minimum fluxes. Advection will result in larger values.

Recent designs for liners at hazardous waste disposal sites specify that double liners be used and that a sand or gravel drainage blanket be placed between the two liners. The drainage blanket drains to sumps or other leachate extraction facilities and serves as an interception zone for free leachate that flows through the upper liner. The primary reason for this design is to minimize advection through the lower liner. If the liners are constructed of a porous material such as clay, molecular diffusion will cause contaminants to migrate through the upper liner into the drainage blanket. If the sand or gravel is not dry, downward diffusive migration will continue in the drainage blanket and into the bottom liner. Passage of contaminants through the bottom clay liner by diffusion will be unavoidable and may occur even when the drainage blanket yields no leachate to the collection system. In a diffusion context, this situation is nearly equivalent to the single-liner case. Thus, the fact that a drainage blank is seen to be properly performing its design function, does not necessarily mean that contaminants are not migrating relatively quickly via diffusion through the bottom liner. The point here is not to argue that properly-constructed double liners with drainage blankets cannot provide a useful degree of additional environmental protection, but rather to emphasize that molecular diffusion is a mechanism of contaminant movement which can not be ignored, even in the design of double liners.

In the foregoing consideration of the implications of diffusion on contaminant migration through clay liners, diffusion coefficient values similar to those found for the cores from the field study were used. Many clay liners at waste disposal sites are formed of compacted local clay, or of local unconsolidated geologic materials mixed with bentonitic clay. Neither the compaction of local clay or bentonite mixtures are expected to produce a material with $Cl^-$ diffusion coefficients more than half an order of magnitude lower than the Tricil clay. In addition, many natural clays and bentonite mixtures contain less solid-phase organic matter and may retard organic compounds less than the Tricil clay. It is expected, therefore, that molecular diffusion through clay barriers will be of general relevance in many clay liner applications.

## CONCLUSIONS

The core in which $Cl^-$ travelled the farthest in the five-year period since the wastes were buried matched very closely the results of the diffusion model using a laboratory-measured diffusion coefficient. For the second and third cores, the matches between field data and the model were good for some parts of the cores, while the model overestimated the concentrations for others. These results indicate that the influence of advection is negligible and that diffusion modeling based on laboratory-determined coefficients provides maximum chloride-migration rates. The fact that the organic compounds migrated a distance of less than 20 cm during five years was justified based on model results using effective diffusion coefficients which were adjusted for the effects of molecular size and adsorption.

The clay deposit at the study site is thick. Therefore, more than 1,000 years will pass before contaminants from the waste will arrive at the aquifer beneath it. When the diffusion model is applied to a 1 m clay liner, however, breakthrough diffusion times for many compounds are less than 10 years and steady state diffusion fluxes can be large. This study suggests that clay liners possessing low permeability will not prevent unadsorbed contaminants from entering, even in the short term, the hydrogeologic domains beneath the liners. Adsorption of organic contaminants may extend the time before breakthrough, but for some of the common priority pollutants, the breakthrough time is only a few decades or less.

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## TABLE 1. CHLORIDE CONCENTRATION DATA

| CORE 1 | | CORE 2 | | CORE 3 | | |
|---|---|---|---|---|---|---|
| DEPTH[a] | $Cl^-$ CONCENTRATION[b] | DEPTH | $Cl^-$ CONCENTRATION | DEPTH | $Cl^-$ CONCENTRATION | POROSITY |
| -15.2 - -7.6 | 1409(1.1465) | -7.6 - 0.0 | 2167(1.0000) | -7.6 - -3.8 | 2100(1.1444) | 0.52 |
| -7.6 - 0.0 | 1229(1.0000) | 0.0 - 7.6 | 1467(0.6770) | -3.8 - 0.0 | 1835(1.0000) | 0.51 |
| 0.0 - 7.6 | 1084(0.8820) | 7.6 - 15.2 | 579(0.2672) | 3.8 - 7.6 | 1545(0.8420) | 0.32 |
| 7.6 - 15.2 | 769(0.6257) | 15.2 - 22.9 | 542(0.2501) | 7.6 - 11.4 | 1315(0.7166) | 0.36 |
| 15.2 - 22.9 | 779(0.6338) | 22.9 - 30.5 | 715(0.3299) | 11.4 - 15.2 | 297(0.1619) | 0.35 |
| 22.9 - 30.5 | 664(0.5403) | 30.5 - 38.1 | 741(0.3419) | 15.2 - 19.1 | 128(0.0698) | 0.37 |
| 30.5 - 38.1 | 459(0.3735) | 38.1 - 45.7 | 390(0.1800) | 19.1 - 22.9 | 58(0.0316) | 0.38 |
| 38.1 - 45.7 | 379(0.3084) | 45.7 - 53.3 | 252(0.1163) | 22.9 - 26.7 | 36(0.0196) | 0.37 |
| 45.7 - 53.3 | 253(0.2059) | 53.3 - 61.0 | 205(0.0946) | 26.7 - 30.5 | 40(0.0218) | 0.39 |
| 53.3 - 61.0 | 167(0.1359) | 61.0 - 68.6 | 85(0.0392) | 30.5 - 38.1 | 24(0.0131) | 0.39 |
| 61.0 - 68.6 | 105(0.0854) | 68.6 - 76.2 | 32(0.0148) | 38.1 - 45.7 | 14(0.0076) | 0.37 |
| 68.6 - 76.2 | 74(0.0602) | | | | | |
| 76.2 - 83.8 | 55(0.0448) | | | | | |
| BACKGROUND | 121+/-8 | BACKGROUND | 213+/-31 | BACKGROUND | 125+/-10 | |

[a] cm below the flyash/clay interface

[b] background subtracted concentrations in mg/L and normalized concentrations in parenthesis

## TABLE II. ORGANICS CONCENTRATION, TOTAL ORGANIC CARBON (TOC), AND SOIL ORGANIC CARBON (SOC) DATA ABSOLUTE (ug/L) AND NORMALIZED (in parenthesis)

### (a) Core 1

| depth interval[a] | benzene | trichloroethene | toluene | ethylbenzene | naphthalene | 1,2-dichloropropane | SOC(g/g of soil) | TOC(mg/L) |
|---|---|---|---|---|---|---|---|---|
| -15.2 - -7.6 | 7920 (2.3432) | 844.0 (2.3123) | 9520 (1.5208) | 3320.0 (1.5660) | 2352.0 (3.0231) | 821.0 (2.7276) | NA[c] | 1112.0 (1.2008) |
| -7.6 - 0.0 | 3380 (1.0000) | 365.0 (1.0000) | 6260 (1.0000) | 2120.0 (1.0000) | 778.0 (1.0000) | 301.0 (1.0000) | NA | 926.0 (1.0000) |
| 0.0 - 7.6 | 283 (0.0837) | 32.7 (0.0896) | 470 (0.0751) | 72.9 (0.0344) | 23.9 (0.0307) | 39.2 (0.1302) | 0.010 | 353.0 (0.3812) |
| 7.6 - 15.2 | 167 (0.0494) | 2.5 (0.0068) | 37 (0.0052) | 1.3 (0.0006) | 0.1 (0.0001)[b] | 9.0 (0.0299) | 0.013 | 149.0 (0.1609) |
| 15.2 - 22.8 | 4 (0.0012)[b] | 0.4 (0.0011)[b] | 9 (0.0014)[b] | 0.8 (0.0004)[b] | 0.1 (0.0001) | 0.3 (0.0010)[b] | 0.012 | 79.0 (0.0853) |
| 22.9 - 30.5 | 4 (0.0012) | 0.4 (0.0011) | 9 (0.0014) | 0.8 (0.0004) | 0.1 (0.0001) | 0.3 (0.0010) | 0.013 | 4.0 (0.0043) |

### (b) Core 2

| depth interval | benzene | trichloroethene | toluene | ethylbenzene | naphthalene | 1,2-dichloropropane | SOC(g/g of soil) |
|---|---|---|---|---|---|---|---|
| -7.6 - 0.0 | 801 (1.0000) | 83.0 (1.0000) | 3628 (1.0000) | 1503.0 (1.0000) | 516.0 (1.0000) | 120.0 (1.0000) | NA |
| 0.0 - 7.6 | 63 (0.0787) | 7.3 (0.0880) | 393 (0.1083) | 168.0 (0.1118) | 109.0 (0.2112) | 11.5 (0.0958) | 0.010 |
| 7.6 - 15.2 | 300 (0.3745) | 5.8 (0.0699) | 175 (0.0482) | 6.6 (0.0044) | 0.2 (0.0004) | 16.5 (0.1375) | 0.013 |
| 15.2 - 22.8 | 4 (0.0054)[b] | 0.4 (0.0048)[b] | 9 (0.0025)[b] | 0.8 (0.0006)[b] | 0.1 (0.0002)[b] | 0.3 (0.0025)[b] | 0.009 |

### (c) Core 3

| depth interval | benzene | trichloroethene | toluene | ethylbenzene | naphthalene | 1,2-dichloropropane | SOC(g/g of soil) |
|---|---|---|---|---|---|---|---|
| -7.6 - -3.8 | 620 (3.7126) | 67.0 (2.9386) | 2230.0 (1.8740) | 755.0 (1.9162) | 76.0 (3.2759) | 198.0 (2.6757) | NA |
| -3.8 - 0.0 | 167 (1.0000) | 22.8 (1.0000) | 1190.0 (1.0000) | 394.0 (1.0000) | 23.2 (1.0000) | 74.0 (1.0000) | NA |
| 3.8 - 7.6 | 122 (0.7305) | 6.5 (0.2851) | 166.0 (0.1395) | 7.6 (0.0193) | 0.2 (0.0086)[b] | 1.9 ( 0.025) | 0.007 |
| 7.6 - 11.4 | 36 (0.2156) | 0.4 (0.0175)[b] | 0.9 (0.0008) | 0.1 (0.0002)[b] | 0.2 (0.0086) | 0.3 (0.0041)[b] | 0.010 |
| 11.4 - 15.2 | 3 (0.0192)[b] | 0.4 (0.0175) | 0.5 (0.0004)[b] | 0.1 (0.0002) | 0.2 (0.0086) | 0.3 (0.0000) | 0.013 |

[a] distance below the interface (cm)

[b] at or below the minimum detectable concentration

[c] not analyzed

TABLE III. SORPTION AND DIFFUSION COEFFICIENT VALUES

| COMPOUND | FREE-SOLUTION DIFFUSION COEFFICIENT D ($cm^2/s$) | ORGANIC CARBON PARTION CONSTANT $K_{oc}$ | CALCULATED PARTITION COEFFICIENT[f] $K_{d,calc}$ | ORGANIC CARBON RETARDATION FACTOR[g] $R_{oc}$ | CALCULATED DIFFUSION COEFFICIENT[h] $D'_{calc}$ ($cm^2/s$) | OBSERVED PARTITION COEFFICIENT[i] $K_d$ | RETARDATION FACTOR[j] R | CALCULATED DIFFUSION COEFFICIENT[k] $D'_{calc}$ ($cm^2/s$) | OBSERVED DIFFUSION COEFFICIENT[l] $D'_{e,c}$ ($cm^2/s$) |
|---|---|---|---|---|---|---|---|---|---|
| chloride | $2 \times 10^{-5}$ [a] | 0.0 | 0.0 | 1.0 | $5 \times 10^{-6}$ | 0.0 | 1.0 | $5 \times 10^{-6}$ | $5 \times 10^{-6}$ |
| [redacted] | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| 1,2-dichloro-propane | $8 \times 10^{-6}$ [c] | 48.[d] | 0.48 | 3.1 | $6 \times 10^{-7}$ | ND[m] | ND | ND | $1 \times 10^{-7}$ |
| ethylbenzene | $6 \times 10^{-6}$ [b] | 870.[e] | 8.70 | 39. | $4 \times 10^{-8}$ | 62. | 269. | $6 \times 10^{-9}$ | $2 \times 10^{-8}$ |
| naphthalene | $6 \times 10^{-6}$ [c] | 940.[d] | 9.40 | 42. | $4 \times 10^{-8}$ | ND | ND | ND | $2 \times 10^{-8}$ |

---

[a] from Li and Gregory (16).

[b] from Binoli and Witherspoon (17).

[c] calculated using Equation 5 and $D = 7 \times 10^{-6}$

[d] from Mabey et al. (21).

[e] using $\log K_{oc} = \log K_{ow} - 0.21$ (Karickhoff (22)) and $\log K_{ow} = 3.15$

[f] $K_{d,calc} = K_{oc} \times SOC$
$= K_{oc} \times 0.01$

[g] $R_{oc} = 1 + (\text{soil bulk density} \times K_{oc} \times SOC) / \text{porosity}$
$= 1 + (1.6 \times K_{oc} \times 0.01) / 0.37$

[h] $D'_{calc} = D \times \mathcal{T} / R_{oc}$
$= D \times 0.25 / R_{oc}$

[i] from the batch sorption experiments at ~1000 ug/L

[j] $R = 1 + (\text{soil bulk density} \times K_d)/\text{porosity}$
$= 1 + (1.6 \times K_d)/0.37$

[k] $D'_{calc} = D \times \mathcal{T} / R$
$= D \times 0.25 / R$

[l] measured in core 1

[m] ND = not determined.

## LIST OF FIGURES

Figure 1. a) Regional map showing the location of the site on the St. Clair clay plain; b) Sarnia area map.

Figure 2. Cross-sectional view of one of the consolidometers.

Figure 3. Semi-log plots of chloride and several organics for core 1.

Figure 4. Semi-log plots of chloride and several organics for core 2.

Figure 5. Semi-log plots of chloride and several organics for core 3.

Figure 6. Linear plots of chloride and several organics in core 1, along with simulation data. Time = 1800 days and diffusion coefficients are indicated on the figure ($cm^2/s$).

Figure 7. Simulations of diffusion into 25 m and 1 m thick clay liners using the times (years) and diffusion coefficents ($cm^2/s$) indicated in the figure.

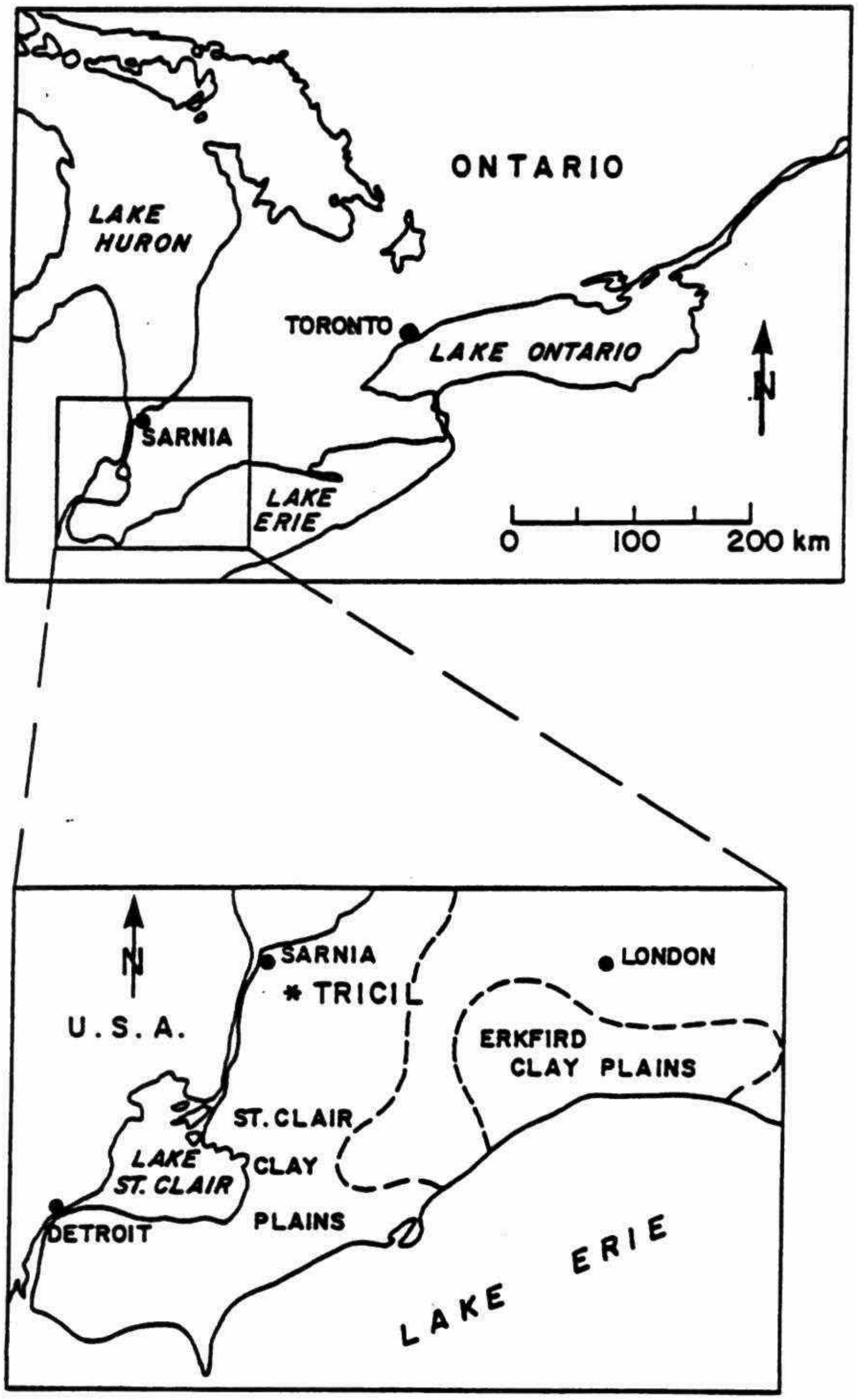

Figure 1. a) Regional map showing the location of the site on the St. Clair clay plain; b) Sarnia area map.

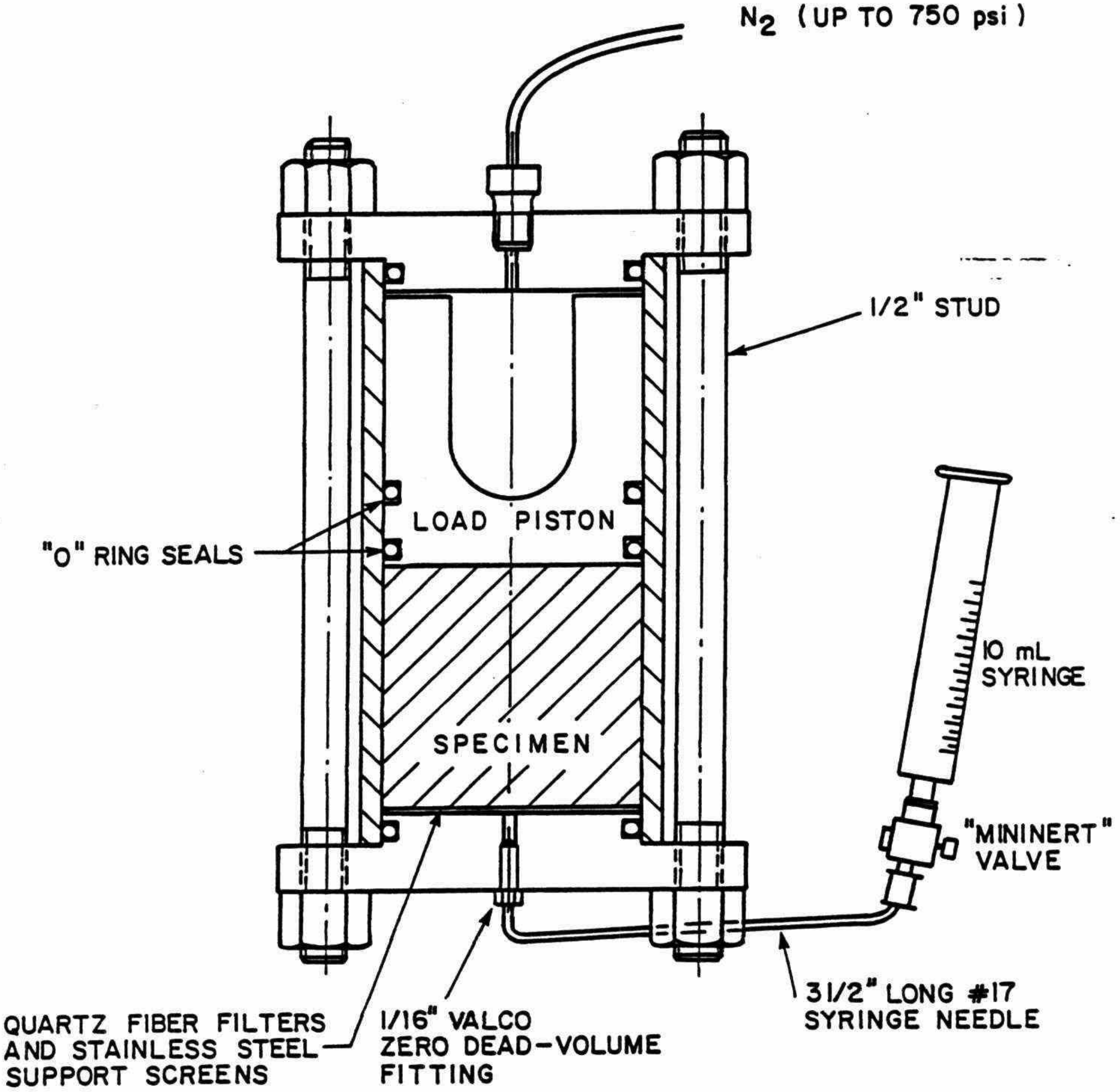
N₂ (UP TO 750 psi)
1/2" STUD
"O" RING SEALS
LOAD PISTON
SPECIMEN
10 mL SYRINGE
"MININERT" VALVE
QUARTZ FIBER FILTERS AND STAINLESS STEEL SUPPORT SCREENS
1/16" VALCO ZERO DEAD-VOLUME FITTING
3 1/2" LONG #17 SYRINGE NEEDLE

Figure 2. Cross-sectional view of one of the consolidometers.

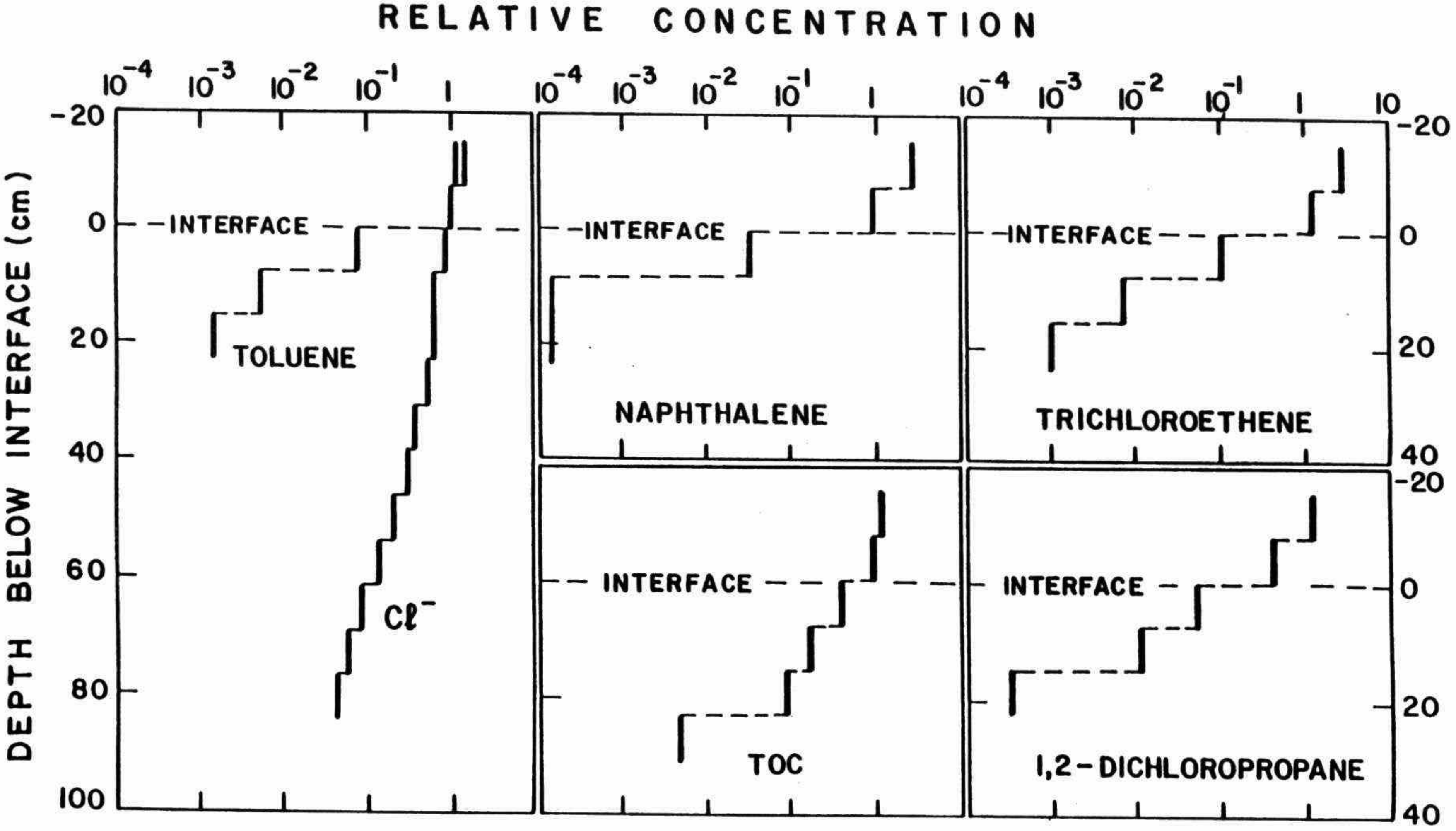

Figure 3. Semi-log plots of chloride and several organics for core 1.

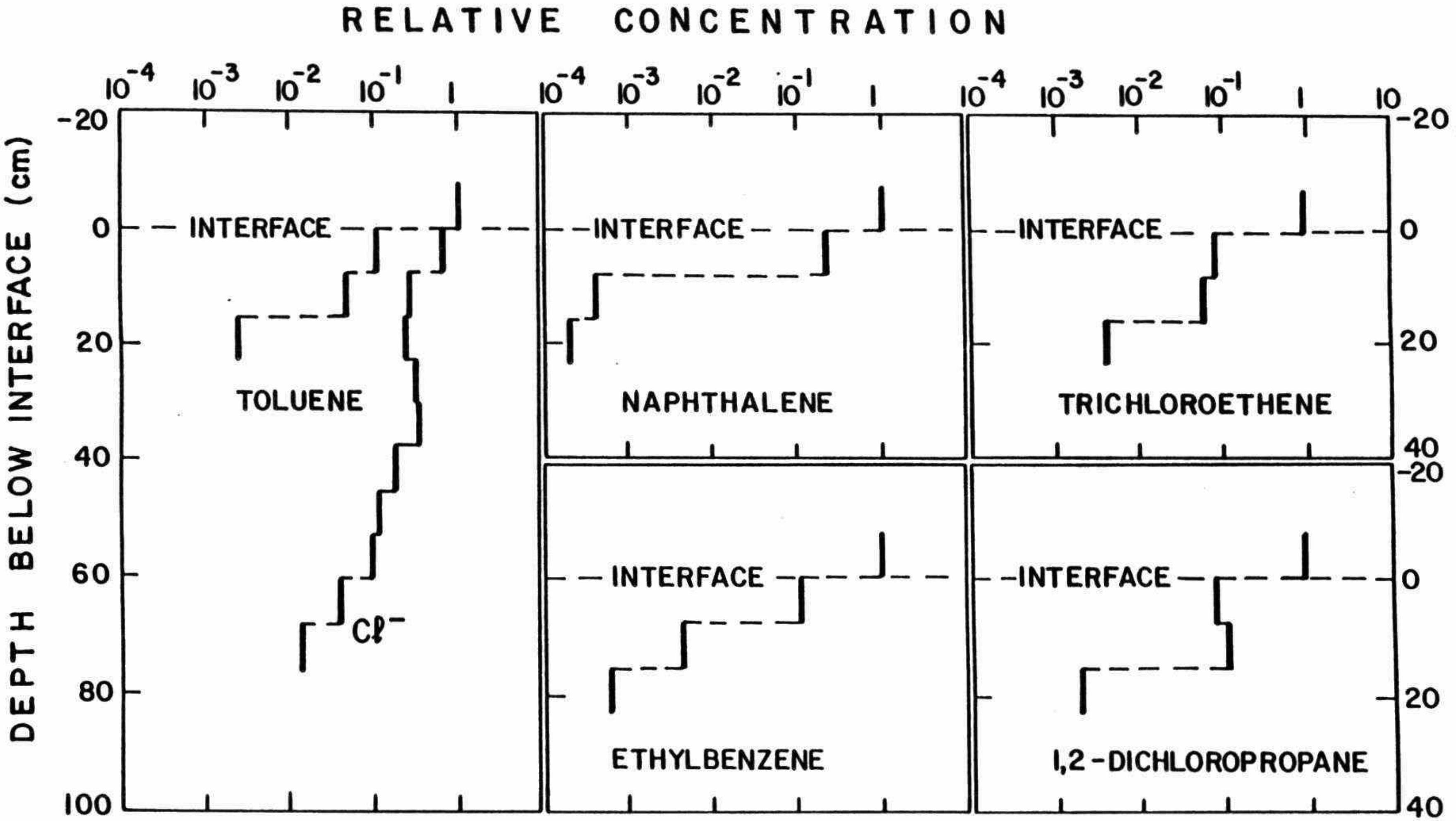

Figure 4. Semi-log plots of chloride and several organics for core 2.

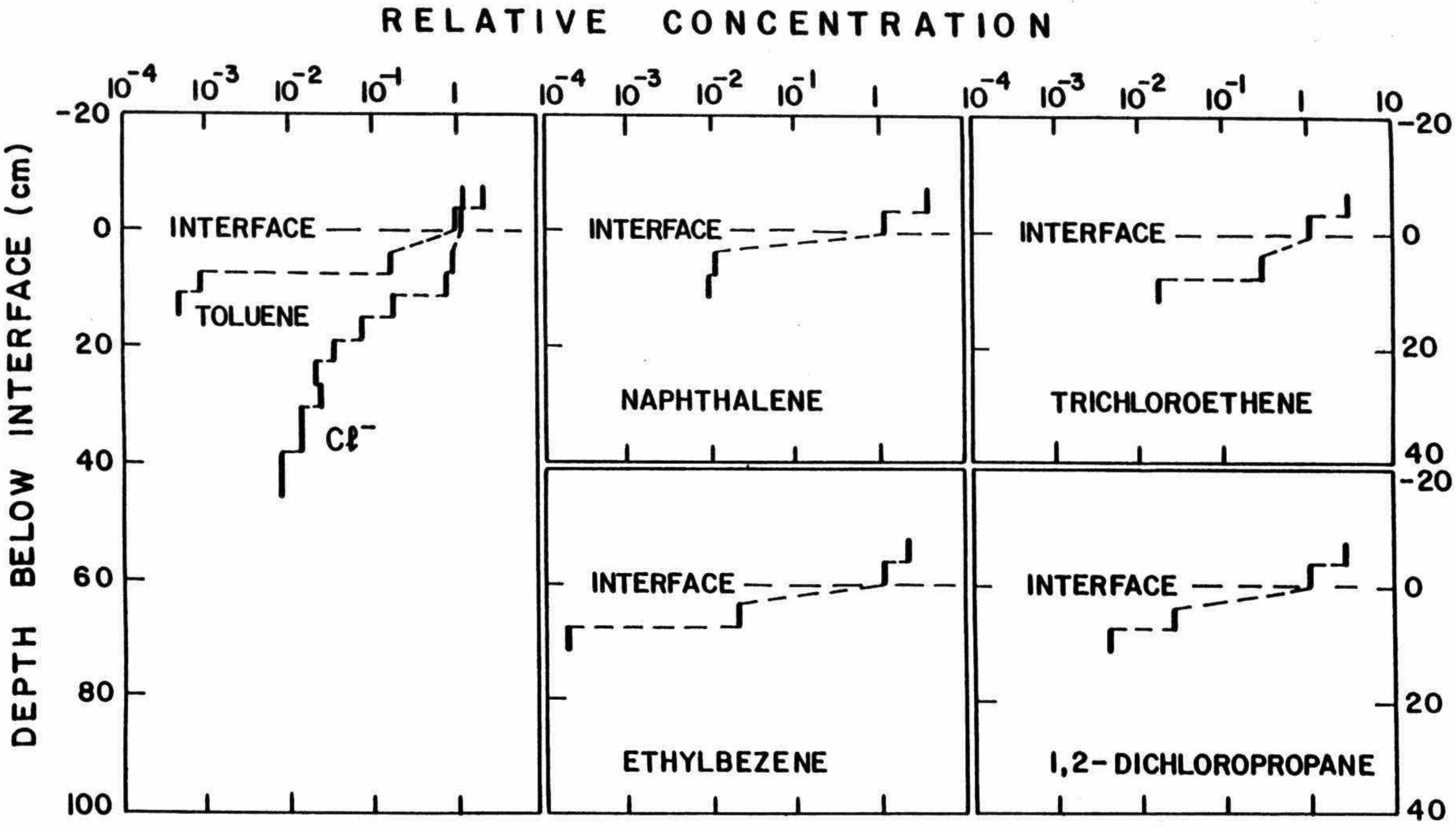

Figure 5. Semi-log plots of chloride and several organics for core 3.

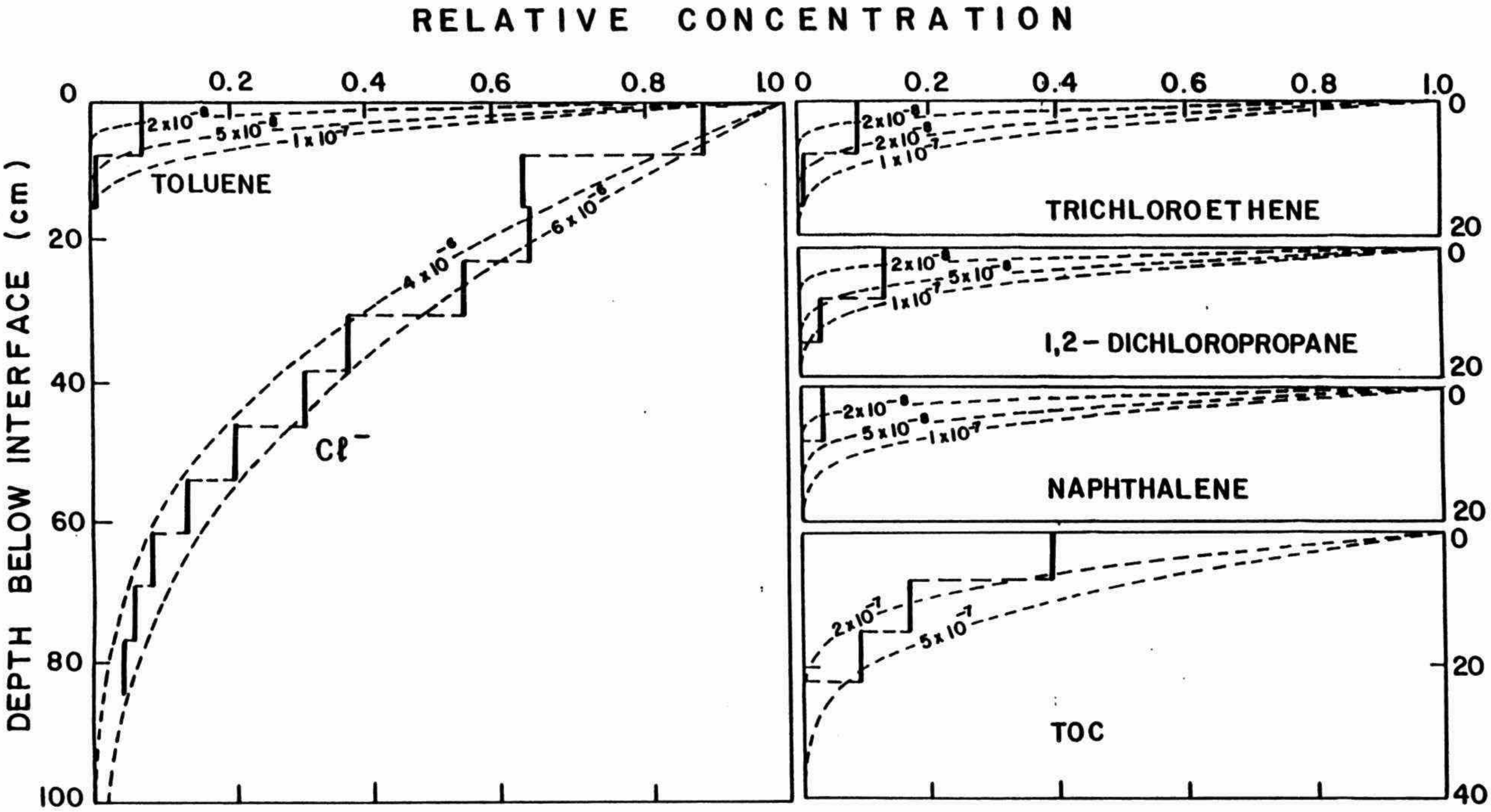

Figure 6. Linear plots of chloride and several organics in core 1, along with simulation data. Time = 1800 days and diffusion coefficients are indicated on the figure ($cm^2/s$).

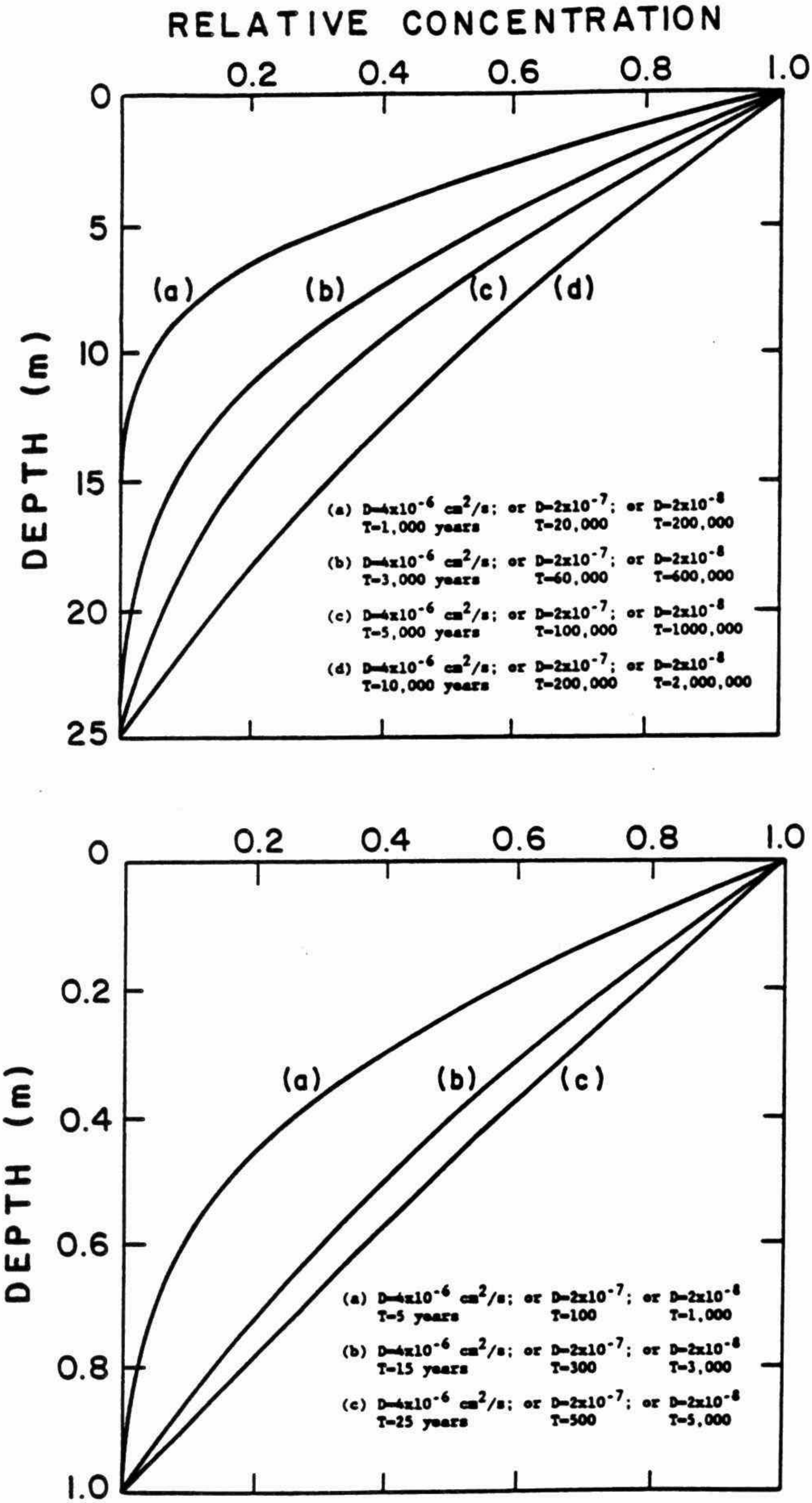

Figure 7. Simulations of diffusion into 25 m and 1 m thick clay liners using the times (years) and diffusion coefficents ($cm^2/s$) indicated in the figure.

# Appendix D

# ROUTINE ORGANIC ANALYSES: METHODS AND QA/QC INFORMATION.

# TOC/DOC (DC-80)

## A. Description and Application

A.1 The DC-80 is a general purpose laboratory TOC/DOC analyzer. It's high sensitivity, combined with wide linear range, allows direct application to samples as diverse as ultra-pure water to heavily contaminated wastewater. The applicable range is 0.18 to 4000 ppm carbon.

## B. Summary of Method

B.1 An acidified persulfate reagant is continuously pumped from an external reservoir to the injection port, then into the UV reactor. The reactor liquid is continuously sparged and this sparge/carrier gas flows out of the reactor to a non-dispersive detector (NDIR). A sample (containing organic carbon) injected into the DC-80 is carried into the reactor by the reagant flow. It is oxidized (by the UV promoted persulfate technique) and the resultant carbon dioxide is sparged from the liquid and carried to the NDIR where the peak (electrical output) is measured.

## C. Sample Handling and Preservation

C.1 Samples are collected in 20ml glass scintillation vials, acidified with 4 drops phosphoric acid, sealed with a tin foil lined cap and stored in a 4 C refrigerator until analyzed. Samples for DOC analysis must be filtered through 0.45 um filter paper. Prior to analysis samples are purged with oxygen carrier gas to eliminate any inorganic carbon dioxide.

## D. Interferences

D.1 Samples with high chloride and sample turbidity result in long run times.

## E. Apparatus

E.1 Dohrman Carbon Analyzer

## F. Reagants

F.1 Potassium Persulfate (45g $K2S2O8$/2 litres organic free water) with 2ml nitric acid added.

F.2 2000 ppm carbon stock (425 +/- 1 mg potassium biphthalate/litre organic free water).

F.3 Organic Free Water.

G. Procedure

G.1 The DC-80 is allowed to warm-up for a minimun of 30 minutes or until a stable baseline is obtained.

G.2 The DC-80 is calibrated at the range most suitable for the expected concentration of samples submitted.

| Range | Injection Vol | Calibration Conc |
|---|---|---|
| 0-20 ppm | 1000 ul | 10 ppm |
| 20-650 ppm | 200 ul | 400 ppm |
| 100-3000 ppm | 40 ul | 2000 ppm |

G.3 Samples are then analyzed by injecting 1000, 200 or 40 ul into the DC-80 (in duplicate) with a calibration check every 10 samples

H. Precision, Accuracy and MDL

| Xo | X | N | S% | E% | MDL |
|---|---|---|---|---|---|
| | | 1000 ul range | | | |
| 2.00 mg/L C | 1.90 | 8 | 3.2 | -4.8 | 0.18 |
| 20.0 mg/L C | 20.52 | 7 | 3.9 | +2.6 | |
| | | 200 ul range | | | |
| 20.0 mg/L C | 20.79 | 10 | 1.8 | +4.0 | |
| 400.0 mg/L C | 403.0 | 8 | 1.0 | +1.0 | |
| 600.0 mg/L C | 644.8 | 8 | 1.0 | +7.4 | |

Xo: true value; X: mean of replicate determinations, 99% confidence level; N: number of replicate determinations; S%: relative standard deviation; E%: average relative error; MDL: method detection limit.

# CHLORIDE (AUTOMATED)

## A. Scope and Application

A.1 This automated method is applicable to drinking, surface and saline waters. The applicable range is 0.2 to 10 mg Cl/L. The range may be extended with sample dilution.

## B. Summary of Method

B.1 Thiocyanate ion (SCN) is liberated from mercuric thiocyanate through sequestration of mercury by chloride ion to form un-ionized mercuric chloride. In the presence of ferric ion, the liberated SCN forms highly colored ferric thiocyanate, in concentration proportional to the original chloride concentration.

## C. Sample Handling and Preservation

C.1 Samples are collected in 20 ml plastic scintillation vials, and stored in a 4 C refrigerator until analyzed.

## D. Interferences

D.1 Acidification of samples results in negative peaks.

## E. Apparatus

E.1 Technicon AutoAnalyzer consisting of the following components: Sampler, Manifold, Colorimeter equipped with a 15mm tubular flow cell and 480 nm filters.

E.2 A recorder.

## F. Reagants

F.1 Saturated Mercuric Chloride, 20.2% Ferric Nitrate, Diluent Water (10 ml/L Brij-35), Distilled Water, Stock Sodium Chloride Standard (1000 mg/L Cl).

## G. Procedure

G.1 The Technicon AutoAnalyzer is set-up following manufacturer's instructions. The colorimeter and recorder are allowed to warm-up for 30 minutes or until a stable baseline (with all reagants running through the system) is obtained.

G.2 A series of standards (10, 8, 6, 4 and 2 mg/L Cl) are prepared by diluting suitable volumes of the chloride stock solution and placed in the sampler in order of decreasing chloride concentration.

G.3 Samples are placed in the sampler tray after making the appropriate dilution if required. A standard series is run after every 20 samples.

## H. Calculations

H.1 A standard curve for each day of analysis is prepared by plotting peak height against concentration for the standard series. The concentration of samples is obtained by comparing sample peak heights with the standard curve.

## I. Accuracy, Precision and MDL

| Xo | X | N | S% | E% | MDL |
|---|---|---|---|---|---|
| 1.0 mg/L Cl | 1.06 +/- .08 mg/L Cl | 11 | 7.4 | +6.0 | 0.21 |
| 5.0 mg/L Cl | 5.48 +/- .13 mg/L Cl | 10 | 2.4 | +9.6 | |
| 50.0 mg/L Cl | 49.7 +/- 1.4 mg/L Cl | 29 | 2.8 | -1.2 | |
| 100.0 mg/L Cl | 95.7 +/- 1.5 mg/L Cl | 10 | 1.4 | -4.3 | |

Xo: true value; X: mean of replicate determinations, 99% confidence level; N: number of replicate determinations; S%: relative standard deviation; E%: average relative error; MDL: method detection limit.

## Miscellaneous Aromatic Hydrocarbons - Analytical Method

APPARATUS. Samples and aqueous standards are extracted in Supelco 60 ml crimp-top hypo-vials with teflon-faced silicone septa. The determinations are performed on a gas chromatograph equipped with a split injection port, capillary column and an FID. The column used is a 0.32 mm x 6 m fused silica type with a 0.25 um bonded DB5 stationary phase. The chromatographic conditions are as follows: injection port temperature = 200 C; initial column temperature = 50 C; initial time = 1 min; heating rate = 10 deg/min; final temperature = 150 C; final time = 0.5 min; detector temperature = 300 C; column flow rate = 5 ml/min helium.

REAGENTS. The following reagents are used: glass distilled pentane and methanol; organic-free deionized water; 10% aqueous sodium azide solution; reagent grade organic solutes (see MDL list).

PROCEDURE. i)SAMPLE BOTTLE PREPARATION. Bottles and other glassware are soaked in a commercial alkaline cleaning solution for several hours, then rinsed with deionized water, dilute nitric acid, and more deionized water. The bottles are then baked overnight at 110 C. Upon removal from the oven, the bottles are covered over with foil. Because the septa can be a major source of contamination, they must be boiled in reagent water for one hour, then baked overnight at 110 C as well.

ii)SAMPLE COLLECTION AND HANDLING. Each sample bottle is filled with no aeration, quickly crimped, then stored on ice until needed. Prior to capping, 500 ul of the sodium azide preservative is injected directly into the water.

To solvent extract a sample (or standard), a vent needle is inserted through the septum, then 1 ml of water is removed with a syringe. With the vent still in place, 500 ul of pentane, containing the internal standard m-fluorotoluene, is added. The vent is then removed and the bottle is agitated on its side at maximum speed on a platform shaker for 10 min. The bottle is inverted and the phases allowed to separate for 10 to 30 more minutes before the sample is analyzed.

The bottle is then righted and approximately 4 ul of the pentane phase removed (with venting) for injection into the chromatograph.

iii)QUALITY CONTROL. The laboratory temperature is maintained at 22 C. Samples and standards are equilibrated to this temperature before extraction.

The gas chromatograph is calibrated by averaging the runs for five standard replicates at approximately 2000 ug/L for each compound.

Two stock standards, one approximately an order of magnitude more concentrated than the other, are independently prepared. The higher concentration is used to calibrate the instrument; the lower one is used as a check, and is routinely run on the GC after every tenth sample. The standard checks were initially prepared at several concentrations in water to establish response linearities and detection limits. Subsequently, during a sampling session they are run at a fixed concentration comparable to that of the unknowns.

A stock standard is prepared gravimetrically, injecting the various pure compounds through a septum into one 60 ml aliquot of methanol. This solution is then diluted further by injecting through a septum into a 60 ml sample bottle filled with reagent water. The standards are extracted and run in the same way as the samples.

Reagent water blanks are run on a daily basis. The stock standards are stored in a freezer when not in use and are replaced when accuracy becomes unacceptable.

## Aromatic Method Detection Limit - 60 ml Hypovials

ug/L

| Compound | N | S% | X | Xo | E% | MDL |
|---|---|---|---|---|---|---|
| Benzene | 10 | 11.6 | 2.77+/-.32 | 2.16 | 22 | 0.90 |
| Toluene | 9 | 24.2 | 2.40+/-.58 | 2.28 | 5 | 1.63 |
| Cl-Benzene | 8 | 12.4 | 2.99+/-.37 | 2.94 | 2 | 1.12 |
| Et-Benzene | 9 | 16.2 | 1.97+/-.32 | 2.19 | -11 | 0.92 |
| p/m Xylene | 10 | 24.7 | 2.35+/-.58 | 2.22 | 6 | 1.63 |
| o-Xylene | 10 | 10.7 | 2.24+/-.24 | 2.22 | 1 | 0.69 |
| Cumene | 9 | 14.1 | 1.91+/-.27 | 2.21 | -16 | 0.78 |
| 1,2,4 TMB | 10 | 11.9 | 2.19+/-.26 | 2.26 | -3 | 0.72 |
| Naphthalene | 10 | 13.8 | 3.11+/-.43 | 2.66 | 14 | 1.20 |

## Aromatic Method Detection Limit - 18 ml Hypovials

ug/L

| Compound | N | S% | X | Xo | E% | MDL |
|---|---|---|---|---|---|---|
| Benzene | 10 | 30.8 | 3.90+/-1.2 | 2.16 | 45 | 3.35 |
| Toluene | 9 | 27.3 | 3.04+/-.83 | 2.28 | 25 | 2.42 |
| Cl-Benzene | 9 | 11.9 | 2.93+/-.35 | 2.94 | 0 | 1.03 |
| Et-Benzene | 7 | 13.0 | 1.85+/-.24 | 2.19 | -18 | 0.76 |
| p/m-Xylene | 9 | 19.3 | 2.54+/-.49 | 2.22 | 13 | 1.43 |
| o-Xylene | 10 | 36.4 | 2.20+/-.80 | 2.22 | -1 | 2.25 |
| Cumene | 9 | 12.5 | 1.60+/-.20 | 2.21 | -38 | 0.57 |
| 1,2,4 TMB | 10 | 16.0 | 1.94+/-.31 | 2.26 | -16 | 0.89 |
| Naphthalene | 10 | 16.0 | 2.50+/-.40 | 2.66 | -6 | 1.13 |

N: number of replicate determinations; S%: relative standard deviation; X: mean of replicate determinations, 99% confidence level, background subtracted; Xo: true value; E%: average relative error; reagant water matrix.

## HALOCARBONS: CHLOROFORM, CARBON TETRACHLORIDE, 1,1,1 TRICHLOROETHANE, TRICHLOROETHYLENE AND TETRACHLOROETHYLENE

## PENTANE EXTRACTION PROCEDURE

### SAMPLE PREPARATION

Samples are collected in 60 ml serum bottles and extracted with 2 ml of pentane (spiked with 800 ppb 1,2-dibromoethane) as outlined in the report by Henderson, J. E., G. R. Peyton and W. H. Glaze. In: Identification and Analysis of Organic Pollutants in Water, L. H. Keith, Ed. (Ann Arbor, MI: Ann Arbor Science Publishers, Inc. 1976) p. 105.

The bottles are shaken for 20 min at 350 rpm with a gyrotory platform shaker to bring the partitioning to equilibrium. A 1 ul aliquot of the organic layer is sampled for chromatographic analysis.

### CHROMATOGRAPHIC ANALYSIS

The extracts are run on a Hewlett Packard 5710A gas chromatograph with a $^{63}$Ni electron capture detector. The column is 8ft x 2mm i.d. glass, packed with 10% squalane on chromasorb P,AW (80/100 mesh). The analysis is run isothermally at 100°C with argon/methane carrier gas at a flow rate of 16 ml/min. The detector temperature is 300°C. Peak areas are measured by a 3390A Hewlett Packard integrator.

Detection limits for these compound are found to be $\leq$ 0.5 ppb (ug/l) using the EPA procedure for Method Detection Limit (MDL).

# PENTANE EXTRACTION - VOLATILE ORGANICS

## METHOD DETECTION LIMIT - Reagant water matrix

| Cmpd | #aliquots | $\overline{X}$ | $X_o$ | S% | E% | MDL |
|---|---|---|---|---|---|---|
| Chloroform | 7 | 1.56±0.14 | 1.41 | 8.9 | +11 | 0.44 |
| 1,1,1 Trichloroethane | 7 | 1.00±0.02 | 1.03 | 2.1 | -2.6 | 0.06 |
| Carbontetrachloride | 7 | 1.00±0.04 | 1.29 | 3.9 | -22 | 0.12 |
| Trichloroethylene | 7 | 1.16±0.03 | 1.08 | 2.3 | +7.0 | 0.09 |
| Tetrachloroethylene | 7 | 2.24±0.06 | 2.17 | 2.8 | +4.0 | 0.20 |

## ACCURACY AND PRECISION AT TYPICAL SAMPLE CONCENTRATION - Reagant water matrix

| Cmpd | #aliquots | $\overline{X}$ | $X_o$ | S% | E% |
|---|---|---|---|---|---|
| Chloroform | 10 | 32.32±0.83 | 29.72 | 2.6 | +5.8 |
| 1,1,1 Trichloroethane | 10 | 21.38±0.36 | 21.78 | 1.7 | -2.0 |
| Carbon tetrachloride | 10 | 28.17±0.41 | 28.43 | 1.5 | -1.0 |
| Trichloroethylene | 10 | 22.62±0.37 | 22.85 | 1.6 | -1.0 |
| Tetrachloroethylene | 10 | 48.45±0.76 | 45.79 | 1.6 | +5.8 |

$\overline{X}$ : mean of replicate determinations, 99% confidence level
$X_o$ : true value
S% : relative standard deviation
E% : relative error
MDL : method detection limit

ANALYSIS OF USEPA QUALITY CONTROL SAMPLE WP1278 - groundwater matrix

| Cmpd | #aliquots | $\overline{X}$ | $X_o$ | S% | E% |
|---|---|---|---|---|---|
| Chloroform | 10 | 62.21±2.48 | 73.0 | 4.0 | -16 |
| 1,1,1 Trichloroethane | 10 | 5.73±0.22 | 8.4 | 3.9 | -32 |
| Carbon tetrachloride | 10 | 11.32±0.32 | 14.0 | 2.8 | -19 |

$X_o$ : EPA value

TD
423
.O32
1989

Environmental research :
research and technology branch
: final report: the occurance
and mobility of hazardous
15197